2022 – 2025

Scientific Report

Center for Theoretical Physics of Complex Systems

Institute for Basic Science

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Chapter 1

Scientific Work and its Organization at the Center – an Overview

1.1 History and Development of the Center

Dec. 2014 - Apr. 2015: The Center for Theoretical Physics of Complex Systems (PCS) was established within the Institute for Basic Science (IBS) in December 2014. After an initial period of the infrastructure setup, the first research fellows joined the PCS in May 2015. Until Jan. 2018, the Center was temporarily hosted at the Munji Campus of KAIST, when we moved into our new premises on the IBS Campus. The founding director *Sergej Flach* launched the scientific activities of the first division, *Complex Condensed Matter Systems*. The concept of the Center includes the setup of three scientific divisions and a Visitor (and Workshop) Program. The Center's mission is to contribute significantly and essentially to the international research field of theoretical physics of complex systems, as well as promote it. Additionally, the Center's concept includes a large active Visitor Program. Its activities include organization of Advanced Study Groups (duration: one to three months) and focused international workshops – with both types of events related to the rapidly developing topics in the area of the physics of complex systems. The Visitor Program and its activities will offer young scientists – from the Center as well other institutions – a fast track contact pathway to the leading international scientists. In this way new developments will be accessible to young scientists at an earlier stage, both serving as an encouragement and facilitating their scientific development substantially.

May 2015 - Dec. 2015: The Center was officially inaugurated by *Doochul Kim*, president of the IBS, during the Inaugural Symposium on July 24, 2015. *Hee Chul Park* joined the PCS as a junior research team leader, establishing the research team *Quantum Many-Body Interactions and Transport*. The Center welcomed its first visitors, including the members of the Advanced Study Group *Many Body Localization and Non-Ergodicity*, and hosted two workshops.

Jan. 2016 - Dec. 2016: Ivan Savenko and *Ara Go* started to lead the activities of two new junior research teams, *Light-Matter Interaction in Nanostructures* and *Strongly Correlated Electronic Systems*, respectively. Three Advanced Study Groups (*Nonergodicity in Quantum and Classical Many Body Systems, Topological States of Light and Beyond, Anderson Localization in Topological Insulators*) performed research at the Center. Three international workshops were held at the PCS. One of our first research fellows – *Gentaro*

Watanabe – accepted a faculty position at Zhejiang University, China.

Jan. 2017 - Dec. 2017: Daniel Leykam – IBS Young Scientist Fellow – joined the PCS and established our first YSF junior research team, *Theoretical Photonics*. Two Advanced Study Groups gathered at the PCS for the collaborative research – *Topological Phases in Arrays of Luttinger Liquid Wires* and *Dissipative Quantum Chaos*. The PCS organized also four international workshops. A PCS research fellow – *Nojoon Myoung* – joined the faculty at Chosun University, Korea.

Jan. 2018 - Dec. 2018: The PCS welcomed two Advanced Study Groups, *Spin-Active Electric Weak Links* and *Edge Reconstruction in Quantum Hall Systems and Topological Insulators*, as well as hosted five international workshops. *Pinquan Qin* – a PCS research fellow – accepted a faculty position at Wuhan University of Technology, China.

Jan. 2019 - Dec. 2019: Juzar Thingna – IBS Young Scientist Fellow – joined the PCS and established our second YSF junior research team, *Nonequilibrium Quantum Thermodynamics*. An Advanced Study Groups gathered at the PCS for the collaborative research – *Functional Spin-Active Mesoscopic Weak Links*. The PCS organized also six international workshops.

Jan. 2020 - Dec. 2020: All planned workshops were rescheduled for 2021 due to the worldwide COVID pandemics. The entire PCS seminar program was moved into online mode including Youtube streaming and recording. One Advanced Study Group *Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links* was conducted in online mode. A second Advanced Study Group *Deep Learning in Quantum Phase Transitions* was moved to 2022, with online PCS seminars held in 2020 and 2021. A PCS junior research team leader – *Ara Go* – joined the faculty at Chonnam National University, Korea. A PCS research fellow – *Ki Hoon Lee* – joined the faculty at Incheon National University, Korea. IBS Young Scientist Fellow *Daniel Leykam* moved to a researcher position at National University of Singapore. All of the above three PCS Alumni joined the new PCS Associate Program.

Jan. 2021 - Dec. 2021: Dario Rosa and *Moon Jip Park* started to lead the activities of two new junior research teams, *Quantum Chaos in Many-Body Systems* and *Topological and Correlated Quantum Matter*, respectively. *Sergei Koniakhin* – IBS Young Scientist Fellow – joined the PCS and established our third YSF junior research team, *Optics of Quantum Fluids and Nanomaterials*. Two Advanced Study Groups gathered at the PCS for the collaborative research – *Computational approaches to correlated systems: Applications to diverse materials* and *Incommensurately stacked atomic layers*. One Advanced Study Group *Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links* was conducted in online mode. The PCS organized also one IBS conference and three international workshops. IBS Young Scientist Fellow *Juzar Thingna* moved to a researcher position at University of Massachusetts at Lowell.

Jan. 2022 - Dec. 2022: Sunghun Park – IBS Young Scientist Fellow – joined the PCS and established our fourth YSF junior research team, *Superconducting Hybrid Quantum Systems*. Five Advanced Study Groups gathered at the PCS for the collaborative research – *Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links*, *Deep Learning in Quantum Phase Transitions*, *Hidden order in incommensurately stacked multilayers*, *Computational methods in transition metal compounds: correlations and magnetism*, and *Entanglement and Dynamics in Quantum Matter*. The PCS organized three international workshops.

Jan. 2023 - Dec. 2023: Dominik Šafránek started to lead the activities of new junior research team, *Quantum Thermodynamics and Information Theory*. Five Advanced Study Groups gathered at the PCS for the collaborative research – *Quantum-Functional Mesoscopic Weak Links*, *Unusual order in incommensurately stacked multilayers*, *Tensor Network Approaches to Many-Body Systems*, *Computational study on strongly correlated low-dimensional magnetic systems*, and *Entanglement and Dynamics in Quantum Matter*. The PCS organized five international workshops. Four team leaders secured faculty positions. PCS junior research team leader – *Ivan Savenko* – joined the faculty at Guandong Technion Israel Institute of Technology, China. PCS junior research team leader – *Hee Chul Park* – joined the faculty at Pukyong National University, Korea. PCS junior research team leader – *Moon Jip Park* – joined the faculty at Hanyang University, Korea. PCS junior research team leader – *Dario Rosa* – joined the faculty at the IFT-Unesp in São Paulo, Brazil.

Jan. 2024 - Dec. 2024: Dung Xuan Nguyen started to lead the activities of the new junior research team, *Topological Quantum Matter*. Two Advanced Study Groups gathered at the PCS for the collaborative research – *Advanced Study Group: Coherent Charges, Spins and Phonons in Superconducting Weak Links* and *Low-dimensional magnetism and quantum phenomena from computational perspectives*. The PCS organized one intercontinental binodal workshop and one international workshop.

Jan. 2025 - Dec. 2025: Three Advanced Study Groups gathered at the PCS for the collaborative research – *Theoretical Challenges of Quantum Magnets with Complex Anisotropies*, *Spin-orbit coupling in transition metal complexes: from model to realistic system*, and *Coherent Charges, Spins and Phonons in Superconducting Weak Links*. The PCS organized also four international workshops. PCS junior research team leader – *Dominik Šafránek* – joined the faculty at Charles University, Czechia. PCS research fellow – *Jae Ho Han* – joined the faculty at Korea Military Academy, Korea. PCS junior research team leader – *Dung Xuan Nguyen* – joined the faculty at International Centre for Interdisciplinary Science and Education (ICISE), Vietnam.

Outlook: The center counts 492 publications, a total of 12813 citations, and an h-index $h = 56$ on Google Scholar. Despite its tremendous success, a continuation with a new division headed by a new director could not be realized by IBS, which is a pity and raises other IBS related questions which are not part of the current report. As a result of the foreseeable retirement of the current director, the PCS is winding down by the end of 2025. Practically all members of the PCS quickly found or are successfully securing new positions in research institutes and universities worldwide. The successful concept of the PCS will continue to exist through its alumni who carry the message into the world. These include twenty three (23!) faculties worldwide, including eight (8!) in Korea, six (6!) in China, and five (5!) in India, but also in Singapore, Vietnam, Brazil, USA, and the Philippines.

1.2 Research Areas and Structure of the Center

At the PCS, we investigate collective phenomena in classical and quantum physics. Out of the planned three divisions, the first one has been established and is headed by *Sergej Flach*. Its research activities span a broad spectrum of topics, and are represented by the scientific focus of several closely collaborating research teams:

- Research team *Complex Condensed Matter Systems* led by *Sergej Flach* and *Alexei Andreanov*: nonequilibrium many-body dynamics, macroscopic degeneracies, flat bands, non-Hermitian physics, optical cavities, and machine learning, with subtopics including exciton-polariton condensates, ultracold atomic gases, photonic waveguide networks, optical microcavities, Fano resonances, spin glasses, topology, frustration, disorder, many body localization, artificial gauge fields, dissipative quantum chaos, open quantum systems.

- Junior research team *Quantum Many-Body Interactions and Transport* led by *Hee Chul Park*: quantum many-body interactions, nonlinear dynamics, disordered systems, mesoscopic electron transport, nano-electromechanical systems.
- Junior research team *Light-Matter Interaction in Nanostructures* led by *Ivan Savenko*: semiconductor microcavities, exciton polaritons, quantum transport, open quantum systems, quantum coherence, dissipative solitons, quantum dots, spins in mesostructures, polariton devices (signal routers, THz sources and detectors, lasers).
- Junior research team *Quantum Chaos in Many-Body Systems* led by *Dario Rosa*: late-time quantum chaos and BGS conjecture, early-time quantum chaos and operator growth, quantum batteries, Many-body localization, quantum many-body scars.
- Junior research team *Topological and Correlated Quantum Matter* led by *Moon Jip Park*: topological and unconventional superconductivity with strong spin-orbit coupling, Moire materials and twistronics, bosonic topological phases in spin systems, nano-device applications of topological materials, aperiodic systems and quasicrystals.
- YSF junior research team *Optics of Quantum Fluids and Nanomaterials* led by *Sergei Koniakhin*: optical properties of nanostructures, optical phonons in nanoparticles and Raman scattering, disorder effects on phonons in nanostructures, non-linear aspects of lattice dynamics in nanoparticles, absorption and elastic scattering of light by nanodiamonds, quantum fluids of light, vortices and solitons dynamics, quantum turbulence, artificial photonic lattices, effects of disorder on quantum fluid dynamics.
- Junior research team *Superconducting Hybrid Quantum Systems* led by *Sunghun Park*: superconducting hybrid nanostructures, states read-out using circuit-QED, Majorana fermions in topological superconductors, magnetic impurities in superconductors, coherent electron transport in mesoscopic systems.
- Junior research team *Topological Quantum Matter* led by *Dung Xuan Nguyen*: strongly correlated electron systems, lattice gauge models, topological phase transitions, fractonic systems, topological properties of Hermitian and non-Hermitian photonic systems, quantum transport and optical response in (multilayer) low dimensional systems.
- Junior research team *Quantum Thermodynamics and Information Theory* led by *Dominik Šafránek*: many-body quantum systems, thermalization, concept of entropy, entanglement, quantum batteries, work extraction, quantum metrology and measurement, quantum information processing.

1.3 Visitor Program

Its envisaged large active Visitor Program makes the PCS a very unique research center within the IBS. The Visitor Program not only organizes regular scientific visits at the Center and manages individual fellowships and scholarships for longer research stays at the PCS, but also organizes yearly several international workshops and advanced study groups.

Fellowships and *scholarships* are available for scientists at all levels of their career – from the Ph.D. students to the sabbatical support for professors – with the duration varying from a few weeks to a few years. The Center hosts several *Advanced Study Groups* per year to foster the exchange between outstanding external scientists and young researchers in residence. Each group is headed by a convener, and consists of a number of long-staying established scientists who focus on a current and important topic in the field of physics of complex systems. To intensify even further the scientific interactions both within Korea and with foreign experts, the PCS hosts yearly several *international (focus) workshops*. Their scientific coordinators carefully select renowned specialists representing a given research area within physics of complex systems, whereas the Visitor Program takes over the entire logistics. *Applications* for the organization of international workshops and advanced study groups – as well as pertinent to research visits, fellowships and scholarships – are evaluated at multiple levels including selection committees with external experts. In 2022 – 2025, 210 (onsite: 162 & online: 48) scientists visited the Center – also within special programs – with the addition of a total of 915 workshop participants. The worldwide COVID pandemics opened new online mode opportunities, including investing into new communication technologies in order to prepare and run hybrid events.

1.4 Diversity

The structure and flexibility of the PCS Visitor Program allow us to support research stays ranging from brief (a few days), through short- (up to a month), to long-term (several months or years), thus suiting the schedule of literally any potential visitor. Moreover, we offer various schemes accommodating very different purposes of research visits, including seminar and colloquium presentations, collaboration meetings, workshop and Advanced Study Group participation, long-term Ph.D. student training, sabbatical stay, etc. Financial and logistics support can be fully customized, thus we can accommodate practically any individual needs of our visitors. As a result, in 2022 – 2025 we hosted scientists from 31 countries.

1.5 Research Networking

In accordance with our aims of scientific excellence and the exchange of knowledge at the highest international level, PCS members enter numerous collaborations, both locally and internationally. Already at the level of the PCS itself, broad scientific interests and active interactions are visible in a number of research achievements resulting from the collaborations between members of different research teams. In the constant search for fruitful collaborations, PCS members are supported by the Visitor Program's efforts in organizing international workshops, advanced study groups and individual visits, resulting in numerous opportunities for scientific interactions.

1.5.1 Local, Institutional and International Networking

Locally, PCS members collaborate on various research topics with scientists from many renowned Korean institutions, including KAIST (Korea Advanced Institute of Science and Technology, Daejeon), Korea University (Seoul), APCTP (Asia Pacific Center for Theoretical Physics, Pohang), KIAS (Korea Institute for Advanced Study, Seoul), POSTECH (Pohang University of Science and Technology, Pohang), KIST (Korea Institute of Science and Technology, Seoul), KRISS (Korea Research Institute of Standards and Science, Daejeon), Yonsei University (Seoul), ETRI (Electronics and Telecommunications Research Institute, Daejeon), UNIST (Ulsan National Institute of Science and Technology, Ulsan), Chungnam National University (Daejeon), Kyungpook National University (Daegu), Pusan National University (Busan), UST (University of Science and Technology, Daejeon), Chosun University (Gwangju), Chonbuk National University (Jeonju), Gyeongsang National University (Jinju), Seoul National University (Seoul), Kongju National University (Gongju), NIMS

(National Institute for Mathematical Sciences, Daejeon), Kyung Hee University (Seoul), Sungkyunkwan University (Seoul), Kangwon National University (Samcheok, Chuncheon, Chung-Ang University (Seoul), Ajou University (Suwon), Pukyong National University (Busan). We also maintain close relations with other IBS centers. In addition, we initiated the PCS Associate Program through which designated alumni (e.g. former team leaders) keep their research ties with PCS members. This program could be extended in the future to other target groups in Korea and abroad.

Institutional networking is currently realized mainly through joint international workshops held predominantly at the PCS. In 2022, the PCS was in charge of the Pioneering symposium *Quantum Geometrical Properties of Flatbands and Experimental Realizations of Flatbands* during the Korean Physical Society (KPS) Spring Meeting, and we organized the International Workshop *Computational Approaches to Magnetic Systems (CAMS-2022)* and the Conference *Advances in The Physics of Topological and Correlated Matter* in cooperation with the APCTP. In 2023, We hosted the Focus program *Numerical Methods in Theoretical Physics 2023* and the International Workshop *Computational Approaches to Magnetic Systems (CAMS-2023)* in cooperation with the APCTP. We organized the International Workshop *Correlation and Topology in Quantum Matter* in cooperation with the KIAS. In 2024, We hosted the Intercontinental Binodal Workshop *Flat Bands and high-order Van Hove singularities* in cooperation with the Max Planck Institute for the Physics of Complex Systems (Germany). In 2025, we organized international workshop *Novel Perspectives in Non-Hermitian Physics: From Condensed Matter to Optical and Beyond* in cooperation with the APCTP.

Internationally, numerous scientific collaborations connect the PCS with many distinguished institutions worldwide, including University of Würzburg (Germany), University of Augsburg (Germany), ICTP (International Centre for Theoretical Physics, Italy), University of Gothenburg (Sweden), Tel Aviv University (Israel), Boston University (USA), Columbia University (USA), University of Massachusetts Boston (USA), Nanyang Technological University (Singapore), Australian National University (Australia), Donghua University (Shanghai, China), Nankai University (China), N.I.Lobachevsky State University of Nizhny Novgorod (Russia), RIKEN (Japan), University of Cape Town (South Africa), Northwestern Polytechnical University (China), Max Planck Institute for the Physics of Complex Systems (Germany), Wuhan University of Technology (China), University of Chile (Chile), Loughborough University (UK), University of Toronto (Canada), University of Maryland (USA), Erevan State University (Armenia), University of Magdeburg (Germany), University of Virginia (USA), University of Bordeaux (France), University of Hamburg (Germany), Aston University (UK), Ural Federal University (Russia), University of Cologne (Germany), Vinca Institute of Nuclear Science (Serbia), Shanghai Jiao Tong University (China), University of Granada (Spain), Massachusetts Institute of Technology (USA), Oslo Metropolitan University (Norway), Indian Institute of Technology (India), UC Louvain (Belgium), Stony Brook University (USA), National Research Council (Italy), Institute for Advanced Study (USA), Insubria University (Italy), Hebrew University (Israel), Institute for High Energy Physics (Spain), IBM (USA), Technical University of Munich (Germany), University of Illinois at Urbana-Champaign (USA), Rzhanov Institute of Semiconductor Physics (Russia), Queens College of CUNY (USA), University of Fribourg (Switzerland), University of Zagreb (Croatia), University of Oldenburg (Germany), Ruhr University Bochum (Germany), ICTP-SAIFR (Brazi), NORDITA (Sweden), Sophia University (Japan), Osaka Univeristy (Japan), Concordia University (Canada), Jagellonian University (Poland), Singapore University of Technology and Design (Singapore), CNR-SPIN (Italy), Universita Degli Studi Dell'Insubria (Italy), Istituto di Fotonica e Nanotecnologie (Italy), Max Planck Institute for the Science of Light (Germany), University of Luxembourg (Luxemburg), Dickinson College (USA), National University of Singapore (Singapore), CNRS (France), Beijing University of Technology (China), Nagoya University (Japan), Univesitat Autonoma de Barcelona (Spain), University of Waterloo (Canada), Pennsylvania State University (USA), ITMO University (Russia), Université Clermont Auvergne (France), Xi'an Jiaotong University (China), Autonomous University of Madrid (Spain), Technical University Braunschweig (Germany), Chalmers University of Technology (Sweden), Karlstad University (Sweden), University of Chicago (USA), Lyon Institute of Nanotechnology (France), Donostia International Physics Center (Spain), Niigata University (Japan), The University of Hong Kong (China), Lancaster University (UK), Raman Institute (India), ASTAR (Singapore), Wuerzburg University (Germany), Shanghai Jiao Tong University (China), Trinity College Dublin (Ireland), Waseda University (Japan), Technische Universität Chemnitz (Germany).

Global collaborative efforts are aiming at focused international cooperation and collaboration which includes conducting joint workshops, student and young postdoc exchange, and other measures in specific research areas. General Agreements for International Cooperation exist with:

- Faculty of Science, University of Zagreb (Croatia) on *quantum and complex systems*, 2018-2025
- Universita Degli Studi Dell'Insubria, Center for Nonlinear and Complex Systems (Como, Italy) on *quantum computing, artificial intelligence and machine learning*, 2021-2024
- OsloMet AI Lab Oslo Metropolitan University (Oslo, Norway) on *quantum systems out of equilibrium*, since 2021
- B. Verkin Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine (Kharkiv, Ukraine) on *condensed matter physics*, 2021-2024

As part of these activities, two student trainees from Kharkiv (Ukraine) and Como (Italy) were researching at PCS for extended periods.

1.5.2 Asian Network on Condensed Matter and Complex Systems

On June 29, 2017, the Abdus Salam International Centre for Theoretical Physics (ICTP, Trieste, Italy) approved the *ICTP Asian Network on Condensed Matter and Complex Systems*. The Network is a system of research groups spanning an entire region, pursuing a common scientific project over an extended period. The network program represents an efficient approach to foster the intensify the interactions between the scientists in the region. ICTP Networks contribute to the ICTP efforts to advance scientific expertise in the developing world, providing scientists from developing countries with the continuing education and skills they need to enjoy long and productive careers.

The *Asian Network* is coordinated by Paul A. Pearce (University of Melbourne, Australia and APCTP Pohang) and Sergej Flach (PCS IBS). Both the PCS IBS and APCTP are the headnodes, with joint Korean Subnet (APCTP-POSTECH, PCS IBS, and CALDES IBS) activity coordinators Ki-Seok Kim (APCTP, POSTECH), Dung Xuan Nguyen (PCS IBS), and Jae Whan Park (CALDES IBS). Further network nodes and the respective node coordinators are:

- Center for Artificial Low Dimensional Electronic Systems, Institute for Basic Science, Pohang, Korea (Han Woong Yeom)

- Institute of Physics, Vietnam Academy of Science and Technology, Hanoi, Vietnam (Tran Minh Tien)
- School of Physics, Suranaree University of Technology, Nakhon Ratchasima, Thailand (Worawat Meevasana)
- National Institute of Physics, University of the Philippines Diliman, Quezon City, Philippines (Cristine Villagonzalo)
- University of Indonesia/BRIN/Bandung Institute of Technology, Indonesia (Aziz Majidi, Ahmad Ridwan Tresna Nugraha, and Agung Nugroho)
- Royal University of Phnom Penh, Cambodia (Tharith Sriv and Sunly Khimphun)

After the global COVID-19 pandemic, network activities resumed. The network currently counts 197 participating scientists. The main activities of the network are research visits between the nodes, amounting so far to 11 visits over a total period of 22 weeks. The *Asian Network* holds a week-long annual school (Vietnam 2023, Thailand 2024, Philippines 2025) with up to 100 students (including the PCS students) and selected PCS team leaders among the lecturers' list. The network also supports workshops, with two conducted to date in Korea (one at the PCS).

1.6 Division Complex Condensed Matter Systems
Director: Sergej Flach

Condensed matter physics is a research field which has a steadily growing impact on an increasing number of branches of everyday life in modern societies. At the same time, it is characterized by an astonishing research progress on all levels – from basic and fundamental research to applications. This feature is due to the field's ability to cross-fertilize various research directions, both from its own broad spectrum – including many-body interactions, nonequilibrium transport, topological insulators, flat bands, spin glasses, graphene – but most importantly also from other fields, such as statistical physics, physics of matter-light interactions, quantum optics and photonics, to name a few. This pattern sets the frame for our endeavours and progress in the understanding of a variety of complex condensed matter systems, and defines the pathway of the activities of the division *Complex Condensed Matter Systems*.

1.6.1 Complex Condensed Matter Systems
Team Leader: Sergej Flach, Alexei Andreanov (deputy)

Research Topics

Nonequilibrium Many-Body Dynamics. Quantum interacting many-body systems are usually assumed to thermalize efficiently. Nonlinear many-body dynamical systems were known to show different outcomes related to the Kolmogorov-Arnold-Moser theorem and Arnold diffusion, due to the presence of invariant tori and the closeness to integrable systems. A plethora of physical systems allows for low-dimensional coherent states (e.g. simply periodic orbits) to persist astonishingly far away from these integrable limits. Recent progress e.g. in the field of many-body localization closes the gap and paves the way to study weakly ergodic and even nonergodic interacting many-body systems. Applications and rewards are expected to be located e.g. in the area of quantum computations. We explore the ways nonlinear dynamics is destroying wave coherence through deterministic chaos, and how many surrogate external ac fields it takes to replace that intricate effect. We started to explore the connection between quantum glasses, many-body localization, nonergodicity and macroscopic degeneracies (see below). We are developing novel techniques to quantitatively and precisely detect the transition from ergodic to nonergodic many-body dynamics, through analyzing the impact of low-dimensional coherent states on the fluctuations at equilibrium. We discovered two classes of thermalization slowing down upon approaching integrable limits through the scaling of the Lyapunov spectrum, which is a one parameter scaling law for long range networks of nonintegrable perturbations, and a two parameter scaling law for short range networks. We explore thermalization or its breakdown (even if incomplete) in various quantum many-body systems, interplay of disorder and interactions, like superconducting pairing, using various numerical and analytical tools, including those based on machine learning methods. Main results:

- *Lyapunov Spectrum Scaling for Classical Many-Body Dynamics Close to Integrability*
  Phys. Rev. Lett. 128, 134102 (2022)
- *Thermalization dynamics of macroscopic weakly nonintegrable maps*
  Chaos 32, 063113 (2022)
- *Delayed Thermalization in Mass-Deformed SYK*
  Phys. Rev. B 106, 245147 (2022)
- *Intermediate super-exponential localization with Aubry-André chains*
  Phys. Rev. B 108, 064204 (2023)
- *Machine learning wave functions to identify fractal phases*
  Phys. Rev. B 108, 184202 (2023)
- *Thermalization slowing down in multidimensional Josephson junction networks*
  Phys. Rev. E Letters 108, L062301 (2023)
- *Thermalization universality-class transition induced by Anderson localization*
  Phys. Rev. Research Letters 6, L012064 (2024)
- *Enhancement of Superconductivity in the Fibonacci Chain*
  Phys. Rev. B 109, 134504 (2024)
- *Dynamical chaos in the integrable Toda chain induced by time discretization*
  Chaos 34, 033107 (2024)
- *The Rosenzweig-Porter model revisited for the three Wigner Dyson symmetry classes*
  New Journal of Physics 26 083018 (2024)
- *From Dyson Models to Many-Body Quantum Chaos*
  Phys. Rev. B 111, 035147 (2025)
- *Observation of prethermalization in weakly nonintegrable unitary maps*
  Fizyka Nyzkykh Temperatur/Low Temperature Physics 51(6), 870-880 (2025)
- *Thermalization slowing down of weakly nonintegrable quantum spin dynamics*
  Phys. Rev. Research 7, 023149 (2025)
- *Shallow quantum circuits are robust hunters for quantum many-body scars*
  European Physical Journal Plus 140, 517 (2025)
- *Prethermalization in Fermi-Pasta-Ulam-Tsingou chains*
  Physical Review E 112, 014206 (2025)

Macroscopic Degeneracies. Systems with macroscopic degeneracies are rare in nature, since the high degree of symmetry or fine-tuning, which is required to support them, is easily destroyed by weak perturbations. However, this also is the reason which makes macroscopic degeneracies attractive. Nowadays, manufacturing technologies can be expected to get close to realizing such symmetries/fine-tuning - perhaps not precisely to the point, but with some control around it. Weak perturbations of such a high symmetry system will typically lift the degeneracy and yield uniquely defined eigenstates and thus physics - which however might or is expected to be qualitatively different for different perturbations. Thus, macroscopic degeneracies could host endpoints of various phase transition lines, and promise rich physics in their close neighbourhood. We focus on two directions. First, we study the flat band physics of corresponding tight-binding networks. Notably, flat bands have been realized experimentally with light dissipative condensates and ultracold atomic gases. We develop flat band generators based solely on the local network properties and the existence of compact localized states. We further study the fate of flat bands and compact localized states under the impact of disorder, external fields, few- and many-body interactions, both on a quantum as well as on a classical (nonlinear) level. Main results:

- *Many-body localization transition from flatband fine-tuning*
  Phys. Rev. B 105, L041113 (2022)
- *Anti-PT flatbands*
  Phys. Rev. A 105, L021305 (2022)
- *Correlated metallic two-particle bound states in Wannier–Stark flatbands*
  Phys. Rev. B 106, 125128 (2022)
- *Strong interlayer coupling and stable topological flat bands in twisted bilayer photonic Moiré superlattices*
  Light: Science Applications 11, 289 (2022)
- *Critical-to-insulator transitions and fractality edges in perturbed flat bands*
  Phys. Rev. B 107, 014204 (2023)
- *Flat Band Induced Metal-Insulator Transitions for Weak Magnetic Flux and Spin-Orbit Disorder*
  Phys. Rev. B 107, 174202 (2023)
- *Critical State Generators from Perturbed Flatbands*
  Chaos 33, 073125 (2023)
- *Conductance transition with interacting bosons in an Aharonov-Bohm cage*
  Phys. Rev. A Letters 108, L010201 (2023)
- *Flux-induced midgap states between strain-engineered flat bands*
  Phys. Rev. B 108, 115148 (2023)
- *Superconductivity with Wannier-Stark Flat Bands*
  Phys. Rev. B 109, 075153 (2024)
- *Compact Localized States in Electric Circuit Flatband Lattices*
  Phys. Rev. B 109, 075430 (2024)
- *Trapping Hard-Core Bosons in Flatband Lattices*
  Phys. Rev. B 109, 245137 (2024)
- *Flat band fine-tuning and its photonic applications*
  Nanophotonics 13, 3925 (2024)
- *Orthogonal flatbands in Hamiltonians with local symmetry*
  J. Phys. A: Math. Theor. 57, 495301 (2024)
- *Flatbands in tight-binding lattices with anisotropic potentials*
  Phys. Rev. B 111, 014201 (2025)
- *Realization and characterization of an all-bands-flat electrical lattice*
  Phys. Rev. B 112, 184309 (2025)

Discrete Time Quantum Walks. To address a growing number of hard fundamental computational tasks, we use a novel unitary map toolbox – discrete-time quantum walks (DTQW). Their highly efficient coding implementation is the key to address suitable hard computational problems with Hamiltonian dynamics, and extend beyond Hamiltonian computational limits. We peeked beyond previous horizons set by the CPU time limits for systems of coupled ordinary differential equations. We obtained results for unprecedented times up to 10^{12}, and thereby shift the old Gross-Pitaevskii horizons by four decades. We are also set to study few- and many-body interacting alternatives using DTQWs. Main results:

- *Logarithmic expansion of many-body wave packets in random potentials*
  Phys. Rev. A Letters 105, L020202 (2022)
- *Lyapunov Spectrum Scaling for Classical Many-Body Dynamics Close to Integrability*
  Phys. Rev. Lett. 128, 134102 (2022)
- *Thermalization dynamics of macroscopic weakly nonintegrable maps*
  Chaos 32, 063113 (2022)
- *Intermediate superexponential localization with Aubry-André chains*
  Phys. Rev. B 108, 064204 (2023)
- *Universal Anderson localization in one-dimensional unitary maps*
  Chaos 33, 083134 (2023)
- *Thermalization universality-class transition induced by Anderson localization*
  Phys. Rev. Research Letters 6, L012064 (2024)
- *Observation of prethermalization in weakly nonintegrable unitary maps*
  Fizyka Nyzkykh Temperatur/Low Temperature Physics 51(6), 870-880 (2025)

Non-Hermitian Physics. Real quantum systems are coupled to the environment since no information can be extracted from completely closed systems. We are interested in understanding how the coupling of a quantum system to the environment modifies the genuine quantum effects. We study the synchronization in networks of interacting exciton-polariton condensates, and their resulting emission spectrum. We also analyze light propagation in the dissipative optical waveguide networks, which are remarkably similar in their mathematical description. Furthermore, we use the transformation optics to optimize the quality factor and the spatial emission profile of optical cavities. Last but not least, we investigate the fate of flat bands (see above) in the non-Hermitian settings. Main results:

- *Impact of non-Hermitian mode interaction on inter-cavity light transfer*
  Photon. Res. 10(5), 1232-1237 (2022)
- *Mesoscopic Mobius ladder lattices as non-Hermitian model systems*
  J. Phys. A: Math. Theor. 55, 224008 (2022)
- *Classification of multiple arbitrary-order non-Hermitian singularities*
  Phys. Rev. A 106, 012218 (2022)
- *Revealing non-Hermitian band structure of photonics Floquet media*
  Science Advances, 8, eabo6220 (2022)
- *Realization of non-Hermitian Hopf bundle matter*
  Communications Physics 6, 273 (2023)
- *Dynamics in non-Hermitian systems with nonreciprocal coupling*
  Phys. Rev. A 108, 052205 (2023)
- *Exceptional classifications of non-Hermitian systems*
  Communications Physics 7, 109 (2024)
- *Realization of geometric-phase topology induced by multiple exceptional points*
  Phys. Rev. A 110, 052221 (2024)

- *Pseudo-Hermitian topology in multiband non-Hermitian systems*
  Phys. Rev. A 111, 042205 (2025)
- *Complex energy structures of exceptional point pairs in two-level systems*
  Europhysics Letters 150, 45001 (2025)
- *Spontaneous Emission Decay and Excitation in Photonic Time Crystals*
  Phys. Rev. Lett. 135, 133801 (2025)
- *Robust exceptional point chains and chirality switch in a vast optical parameter space*
  Phys. Rev. A 112, L031501 (2025)

More. Various other research activities enrich and cross-fertilize the work of the team. These include pertinent questions of dense sphere packing, and range from fundamental physics to education, among others. Main results:

- *The egg steamer paradox*
  Phys. Educ. 57, 025002 (2022)
- *Nonlinear dynamics of superposition of wavepackets*
  Eur. Phys. J. Plus 137, 471 (2022)
- *Frequency Map Analysis of Spatiotemporal Chaos in the Nonlinear Disordered Klein–Gordon Lattice*
  International Journal of Bifurcation and Chaos 32(5), 2250074 (2022)
- *Intermediate statistics in singular quarter-ellipse shaped microwave billiards*
  J. Phys. A: Math. Theor. 55, 314001 (2022)
- *Unidirectionality and Husimi functions in constantwidth neutrino billiards*
  J. Phys. A: Math. Theor. 55, 474003 (2022)
- *Distributions of the Wigner reaction matrix for microwave networks with symplectic symmetry in the presence of absorption*
  Phys. Rev. E 107, 024203 (2023)
- *Semi-Poisson Statistics in Relativistic Quantum Billiards with Shapes of Rectangles*
  Entropy 25(5), 762 (2023)
- *Experimental study of the elastic enhancement factor in a three-dimensional wave-chaotic microwave resonator exhibiting strongly overlapping resonances*
  Phys. Rev. E 107, 054210 (2023)
- *Estimation of correlation matrices from limited time series data using machine learning*
  Journal of Computational Science 71, 102053 (2023)
- *Time-reversal invariance violation and quantum chaos induced by magnetization in ferrite-loaded resonators*
  Eur. Phys. J. Spec. Top. (2023)
- *Graphene billiards with fourfold symmetry*
  Phys. Rev. Research 5, 043028 (2023)
- *Ferromagnetic monolayer with interfacial Dzyaloshinskii-Moriya interaction: Magnon spectrum and effect of quenched disorder*
  Phys. Rev. B 108, 174414 (2023)
- *Magnons in the fan phase of anisotropic frustrated antiferromagnets*
  Journal of Magnetism and Magnetic Materials 589, 171544 (2024)
- *Operator dynamics in Lindbladian SYK: A Krylov complexity perspective*
  J. High Energ. Phys. 2024, 94 (2024)
- *Computing Quantum Mean Values in the Deep Chaotic Regime*
  Phys. Rev. Lett. 132, 260401 (2024)

- *Haldane graphene billiards versus relativistic neutrino billiards*
  Phys. Rev. B 110, 094305 (2024)
- *Manifestation of Luttinger liquid effects in a hybrid metal-semiconductor double-quantum dot device*
  Low Temp. Phys. 50, 1180–1188 (2024)
- *Unsupervised techniques to detect quantum chaos*
  Low Temp. Phys. 50, 1127-1134 (2024)
- *Experimental test of an extension of the Rosenzweig-Porter model to mixed integrable-chaotic systems experiencing time-reversal invariance violation*
  Chinese Physics B, 33, 120501 (2024)
- *Observation of magnetic skyrmion lattice in Cr0.82Mn0.18Ge by small-angle neutron scattering*
  Scientific Reports 15, 2865 (2025)
- *Thermal lifetime of breathers*
  Physica D 473, 134551 (2025)
- *Decay rates of optical modes unveiling the island structures in mixed phase space*
  Phys. Rev. A 111, 033509 (2025)
- *Shallow quantum circuits are robust hunters for quantum many-body scars*
  Eur. Phys. J. Plus 140, 517 (2025)
- *Failure of the Conformal-Map Method for Relativistic Quantum Billiards*
  Phys. Rev. Lett. 135, 030401 (2025)
- *Experimental study of the distributions of off-diagonal scattering-matrix elements of quantum graphs with symplectic symmetry*
  Phys. Rev. E 112, 034208 (2025)
- *Instability of Metals with Respect to Strong Electron-Phonon Interaction*
  Phys. Rev. Lett. 135, 026503 (2025)

Perspectives

The team research consolidated during the report period around the main themes listed above. On the team level, we plan to extend the activities in all directions, in particular in the field of discrete time quantum walks and perturbed/interacting flatbands. On the division level, we broadened our spectrum with attractive projects in the field of strong electronic correlations, topological and non-Hermitian photonics, as well as nonequilibrium quantum thermodynamics. One of our next goals is to expand our spectrum of activities by adding the fields of quantum information and machine learning. This can happen both through consolidating the existing research and establishing a new team.

Cooperations

Within the PCS, we collaborate with all junior research teams. Strong cooperations inside Korea include non-Hermitian optics (Pusan National University, Busan; KAIST, Daejeon; Kyungpook National University, Daegu; NIMS, Daejeon).

International cooperations include geometric frustration (University of Bordeaux, France), spin-glasses (University of Oldenburg, Germany), non-Hermitian physics (National Technical University of Athens, Greece; University of Patras, Greece; Columbia University, USA; UNAM, Mexico), flat bands (Concordia Univerisity, Canada; Technion - Israel Institute of Technology; Tel Aviv University, Israel; Nanyang Technological University, Singapore; Tbilisi State University, Georgia; University of Belgrade, Serbia; San Francisco State University, USA; Nankai University, China; University of Innsbruck, Austria; Kirensky Institute of

Physics, Russia; University of Magdeburg, Germany; Erevan State Universitry, Armenia), many-body dynamics (Augsburg University, Germany; University of Trento, Italy; Boston University, USA), non-Gibbs states in many-body interacting systems (JINR, Russia), and few-body interactions (N.I.Lobachevsky State University of Nizhny Novgorod, Russia).

1.6.2 Quantum Many-Body Interactions and Transport

Team Leader: Hee Chul Park

Research Topics

Our research focuses on the quantum transport of mesoscopic systems and the quantum many-body interactions with mean-field theory. 2D materials, including graphene, have been intensively studied in condensed matter physics regarding the optical, electrical, and mechanical degrees of freedom. The spin-orbit interaction impacts a number of well-known physical phenomena, such as the Kondo effect, interference, and Coulomb blockade. Furthermore, coupling with the environment unveils new phenomena in the field of non-Hermitian Hamiltonian physics.

Graphene and 2D materials. 2D materials – including graphene – have been studied extensively during the past decades due to their unique electrical properties originating from the gapless and linear Dirac cone dispersion at the corners of the 1st Brillouin zone. Its prominent transport behavior, such as high carrier mobility, makes graphene a promising candidate material to succeed silicon in the nanoelectronic industry. We have studied the effect of strain on the 2D materials and graphene quantum Hall systems for realizing valleytronics using pseudo-gauge field. The strain on graphene creates a strong pseudo-magnetic field due to the gauge potential acting on the valley-isospin of graphene. The bound states at the locally strained region can be a candidate of graphene qubit and recognized by the machine learning algorithm. In addition to the strain qubit, twisted bilayer graphene hosts the higher-order topological corner states. The states can be a noble qubit as a topological qubit controlled by electric gate potential and measured by quantum interference through electron transport.

- *Magnetism in twisted triangular bilayer graphene quantum dots*
  Phys. Rev. B 111, 024417 (2025)
- *Engineering high Chern number insulators*
  Journal of the Korean Physical Society, 85, 661 (2024)
- *Detecting Strain effects due to nanobubbles ingraphene Mach-Zehnder interferometers*
  Phys. Status Solidi B, 261, 2300379 (2024)
- *Electronic Mach-Zehnder interference in a bipolar hybrid monolayer-bilayer graphene junction*
  CARBON, 201, 734 (2023)
- *Strain-induced flat bands in hexagonal quantum dot networks of graphene nanoribbons with nanobubbles*
  Journal of the Korean Physical Society, 83, 692 (2023)
- *A strain-engineered graphene qubit in a nanobubble*
  Quantum Sci. Technol., 8, 025012 (2023)
- *Machine learning approach to recognition of a nanobubble in graphene*
  Appl. Phys. Lett., 119, 193103 (2021)
- *Electronic states of graphene quantum dots induced by nanobubbles*
  Journal of the Korean Physical Society 78, 1208-1214 (2021)

- *Higher-Order Topological Corner State Tunneling in Twisted Bilayer Graphene*
  CARBON, 174, 260 (2021)
- *Manipulation of valley isospins in strained graphene for valleytronics*
  CARBON, 157, 578 (2020)
- *Decelerated Hot Carrier Cooling in Graphene via Nondissipative Carrier Injection from MoS2*
  ACS nano, 14, 13905 (2020)
- *Splitting of conductance resonance through a magnetic quantum dot in graphene*
  Phys. Rev. B, 100, 045427 (2019)

Nano-electromechanical systems. This is one of the most attractive research fields in physics – both theoretically and experimentally. The improvements in fabrications have opened possibilities for new technologies. Since the quick changes in technology require extremely sensitive sensors to measure low power signals, the limitations of present sensors need to be understood for practical purposes. Studying the interplay between the classical and the quantum mechanical effects under external stimuli, such as electromagnetic fields with environmental conditions, is necessary in order to understand the mechanical motion of mesoscopic systems, e.g., mechanical cantilevers. Quantum measurements related to the nano-electromechanical systems (NEMS), which combine an electronic system with mechanical degrees of freedom, yield another important topic in condensed matter physics. These systems show a variety of nonlinear phenomena, such as self-excited oscillations, spontaneous symmetry breaking, *etc.*, on which our team has published several papers.

- *Nanomechanical Switch toward Electron Turnstile Operation*
  Nano. Lett., 25, 11947 (2025)
- *Diamond Molecular Balance: Ultra-Wide Range Nanomechanical Mass Spectrometry from MDa to Tda*
  Nano. Lett., 25, 10497 (2025)
- *Andreev probing of a Cooper-pair flying qubit*
  Phys. Rev. B, 111, 165404 (2025)
- *Role of Chiral symmetry in a kicked Jaynes-Cummings model*
  Phys. Rev. A, 107, 013712 (2023)
- *Pumping and Cooling of Nanomechanical Vibrations Generated by Cooper-Pair Exchange*
  J. Low Temp. Phys. 210, 150 (2022)
- *Nanomechanical Cat states generated by a dc voltage-driven Cooper pair box qubit*
  npj Quantum Information, 8, 74 (2022)
- *Nanomechanics driven by the superconducting proximity effect*
  New J. Phys., 24, 033008 (2022)
- *Cooling of nanomechanical vibrations by Andreev injection*
  Low Temp. Phys., 48, 476 (2022)
- *Kick-induced rectified current in symmetric nanoelectromechanical shuttle*
  Phys. Rev. B, 104, 064303 (2021)
- *Nanomechanics driven by Andreev tunneling*
  Phys. Rev. B, 102, 235402 (2020)
- *Spin-Polaronic Effects in Electric Shuttling in a Single Molecule Transistor with Magnetic Leads*
  Physica E, 122, 114151 (2020)

- *Electronic current in a nano-mechanical kicked electron shuttle*
  Physica E, 117, 113835 (2020)
- *Kondo effect in Aharonov-Casher interferometer*
  Phys. Rev. B, 100, 235413 (2019)
- *DC spin generation by junctions with AC driven spin-orbit interaction*
  Phys. Rev. B, 100, 115406 (2019)
- *Coulomb Effects on Thermally Induced Shuttling of Spin-polarized Electrons*
  Low Temp. Phys., 45, 1208 (2019)
- *Coulomb-promoted spintromechanics in magnetic shuttle devices*
  Phys. Rev. B, 100, 045408 (2019)

Quantum transport. We are interested in the fundamental quantum effects such as the quantum resonances, quantum chaos, dynamical localization, the chirality of dynamic states, bulk-boundary correspondence of topological systems, and non-Hermiticity. From graphene to ultra-cold atoms, from the prototypes of the simplest to the most exotic materials, we will continue our efforts to understand the fundamental properties of various research topics in mesoscopic physics. All of our topics will be interconnected and realized through specific experimental systems and collaborations between the members of our team and external groups. Since we believe that many new scientific findings emerge from the interplay of basic principles or concepts and their realizations, we expect that the results of our research will not only answer fundamental questions but also lead to even more fundamental questions. It is not only constrained by electronic transport. Still, it can be realized by photonic crystal due to the topological analogy between quantum transport on an atomic lattice and wave propagation on a photonic lattice.

- *Pseudo-Hermitian topology in multiband non-Hermitian systems*
  Phys. Rev. A, 111, 042205 (2025)
- *Orthogonal flatbands in Hamiltonians with local symmetry*
  J. Phys. A, v.57, 1751 (2024)
- *Exceptional classifications of non-Hermitian systems*
  Comm. Phys., 7, 109 (2024)
- *Realization of non-Hermitian Hopf bundle matter*
  Comm. Phys, 6, 273 (2023)
- *Bloch Theorem Dictated Wave Chaos in Microcavity Crystals*
  Light Sci. Appl., 12, 106 (2023)
- *Bloch Theorem Dictated Wave Chaos in Microcavity Crystals*
  Light Sci. Appl., 12, 106 (2023)
- *Revealing non-Hermitian band structure of photonic Floquet media*
  Sci. Adv., 8, eeabo6220 (2022)
- *Strong interlayer coupling and stable topological flat bands in twisted bilayer photonic Moiré superlattices*
  Light Sci. Appl., 11, 289 (2022)
- *Topological edge states in bowtie ladders*
  Physica E, 137, 114941 (2021)
- *Non-orientability induced PT phase transition in ladder lattices*
  Phys. Rev. A 103, 042207 (2021)
- *Emergent localized states due to the twofold PT symmetry in ladder lattice*
  Phys. Rev. Research, 2, 033149 (2020)

- *Flat-band localization and self-collimation of light in photonic crystals*
  Sci. Rep., 9, 2862 (2019)

Perspectives

Our research team was formed in May 2015 with Pinquan Qin and the team leader Hee Chul Park, and now consists of seven collaborating members, including an associate member, Jung-Wan Ryu, and two students, JungYun Han and Olha Bahrova. Sungjong Woo is interested in the strain engineering on low dimensional materials for topological polarization. Anton Parafilo's main research interest is the nanomechanical system, including the Kondo effect and spin-orbit interaction. Jung-Wan Ryu is an expert in nonlinear oscillatory systems and microcavities. Jae-Ho Han studies quantum field theory for condensed matter physics such as spin dynamics and topological superconductivity. Mohamad Mirzakhani works on the electronic properties of hybrid graphene systems. Chang-Hwan Yi is working on quantum chaos in microcavity for . We have two students: JungYun Han is studying thermal transport and qubit, and Olha Bahrova is interested in quantum transport in hybrid nanomechanical systems. All the members work collaboratively on the convergence of each topic, which has recently attracted a lot of interest as an emergent research field. The focus of our team is to study the overall theory behind various topics in fundamental condensed matter physics, such as topological properties, many-body interactions, and quantum phase transitions. The alumni are Pinquan Qin (Professor at Wuhan University of Technology, China), Nojoon Myoung (Professor at Chosun University, Korea), Kun Woo Kim (Professor at ChungAng University), Sang-Jun Choi (postdoctoral researcher at Wuertsburg University, Germany), Wulaimu Maimaity (postdoctoral researcher at Rutgers University), and Ilias Amananditis (postdoctoral researcher at Ben-Gurion University of the Negev, Israel). They still keep collaborating intensely with the team.

Collaborations

We have numerous collaborators with various universities and institutes worldwide outside of our Center. For theoretical studies, we work with: KIAS, Korea (Young Woo Son – graphene & 2D materials); Chosun University, Korea (Nojoon Myoung – graphene, photonics); UST, Korea (Sejoong Kim – time-dependent spin-orbit interaction and spintronics); POSTECH, Korea (Ki-Seok Kim – TI with magnetic disorder); APCTP, Korea (Jaeyoon Cho – bulk-boundary correspondence); University of Gothenburg, Sweden (Robert Shekhter – nano-electromechanical shuttle); University of Ioannina, Greece (Elefterios Lodorikis – graphene optics); Donghua University, China (Binhe Wu – topological insulator with disorder); Wuhan University of Technology, China (Pinquan Qin – dynamic localization); University of Chile (Luis E. F. Foa Torres – non-Hermitian systems and Floquet graphene). We also have experimental collaborators: KIST, Korea (Chulki Kim – nanomechanics, strained graphene); KRISS, Korea (Suyong Jung – graphene VHJ, Seung-Bo Shim and Junho Suh – nanomechanics, Myoung-Ho Bae – Quantum transport); KAIST,Korea (Bumki Min – Realization of non-hermitian topoelectrical circuits); Yonsei University, Korea (Jaehoon Kim – TI, meta-materials, and mesoscopic systems); Chungnam National University, Korea (Young-Jun Yu – graphene gas sensors); UNIST, Korea (Minkyung Jung – graphene transport); Chonbuk National University, Korea (Hyung-Kook Choi – 2DEG with strong SOI); Gyeongsang National University, Korea (Youngwoo Nam – suspended graphene); Kyoung Hee University, Korea (Young-Duck Kim – Graphene and 2D materials).

1.6.3 Light-Matter Interaction in Nanostructures
Team Leader: Ivan Savenko

By the beginning of 2022, the team consisted of 4 members: the junior research team leader, *Ivan Savenko* and three Ph.D. students, *Meng Sun*, *Dogyun Ko*, and Ms. *Kabyashree Sonowal.* We also actively collaborated with Dr. *Anton Parafilo* from PCS.

- With my (now graduated) PhD student, *Meng Sun,* we reported a direct observation of a single quantized vortex vanishing from a microcavity exciton-polariton superfluid. From the time-resolved spectroscopy measurements utilizing various Laguerre-Gaussian beam sizes, our experimental collaborators found that the two lowest-energy states get populated and compete with each other.
  – Physical Review B 105, L060502 (2022)

- With *Dr. A. Parafilo*, we showed that in a two-dimensional noncentrosymmetric Ising superconductor in a fluctuating regime under the action of a uniform external electromagnetic field, there emerge two new contributions to the photogalvanic effect due to the trigonal warping of the valleys. Furthermore, a second-harmonic generation effect might take place. There emerge two contributions to this effect, one conventional, which is due to the electron gas in its normal state, and the other one is of the Aslamazov–Larkin nature.
  – Physical Review B 106, 144502 (2022)
  – 2D Materials 2, 045004 (2023)
  – Physical Review B 108, L180509 (2022)

- With my (now graduated) PhD student, *Kabyashree Sonowal,* we suggested that when exposed to surface acoustic waves, the emerging strain-induced effective magnetic fields in 2D semiconductors can give rise to spin-flip transitions between the spin-split subbands in the vicinity of the subband crossing point, resulting in the emergence of a spin-acoustic resonance and the acoustoelectric current.
  – Physical Review B 106, 155426 (2022)

Future Prospects

The group ended its existence in December, 2023, thus, there are no future prospects.

1.6.4 Quantum Chaos in Many-Body Systems
Team Leader: Dario Rosa

Research Topics

The common theme in the research of this team is to understand how quantum chaos (or its absence) affects the physics of quantum many-body systems. In parallel, another main theme of research has been toward applying this acquired knowledge to the broad field of quantum technologies and quantum thermodynamics. With this general overview in mind, here are the main research results that have been obtained during the reported period.

Investigation in quantum chaos and its violations. Historically, quantum chaos has been described via the so-called Bohighas-Giannoni-Schmit conjecture, which in a nutshell states that quantum chaos can be detected by studying the spectral properties of the energy levels of the system under investigation. This point of view has been heavily tested, both in single-particle problems and in many-body setups. It leads to the notion of quantum universality, *i.e.* to the idea that at very late times the dynamics of a quantum chaotic system is universal and completely determined by its symmetries. In more recent days, an alternative description of quantum chaos, particularly focused towards *many-body* systems, has become very popular. This second approach is based on the notions of *operator scrambling* and *operator growth*, *i.e.* with the intuitive idea that under time evolution local and simple operators evolve towards extended and complex operators.

Arguably, the most significant result obtained by the team in this respect is the introduction of the concept of *operator delocalization* in quadratic systems, which was developed in collaboration with Prof. Murugan, among others. By this term, we refer to a precursor of the physics of scrambling, in which operator growth is absent but large operators are delocalized by the dynamics induced by a quadratic Hamiltonian. This notion has been linked to the charging performance of the SYK quantum batteries (see later), thereby establishing an interesting connection between quantum chaos and potential applications in quantum technologies. In a subsequent paper, we have studied the relation between many-body and single-particle quantum chaos, using a many-body system with a well-defined single-particle origin. In this study, which technically required large-scale sparse diagonalization techniques, we have shown the intimate relation between single-particle chaos and its many-body counterpart. This model can also be seen as a toy model for further investigation into the physics of many-body localization.

Remaining in the field of quantum systems, the team has investigated the localization/delocalization transition in models with disorder. Using the so-called mass-deformed SYK model, a variation of the SYK model including a random mass term, we have studied the Fock space localization transition shown by this system as a function of the mass term parameter. Our results show that before entering the Fock space localized regime, the model has a huge regime of *delayed thermalization*, which can be captured by studying the spectral form factor of the model. At the level of methodologies, we have also studied the possibility of using machine learning techniques to detect the delocalization/localization transition in quantum systems. The main focus has been on the possibility of reusing a certain neural network model, trained on a known system displaying a localization transition, to detect the localization transition in new and unknown systems *without further retraining.* The results obtained are encouraging, and they raise machine learning algorithms to the status of actual convenient tools for studying localization physics. Other works include: an investigation of the well-known Rosenzweig-Porter model and its phase structure using new diagnostics of quantum chaos and localization, and a study of the localization transition in a family of random graphs using unsupervised machine learning techniques.

Another line of research that we have pursued is the analysis of variational quantum algorithms to target states of quantum many-body systems. Among the results, we mention: a study of the possibility of targeting *quantum many-body scars* using *shallow* variational circuits, a characterization of the best depth of a variational shallow circuit in terms of its quantum chaotic properties, a benchmark of the capacity of current quantum machines to generate random quantum states, and a study of the connection between the dynamics of entanglement and classical complexity.

Finally, we studied analytically a *non-Hermitian* (but *PT*-symmetric) version of the SYK model. Our results show that given a replica symmetry breaking phenomenon, which occurs due to the non-Hermitian character of the model, the dynamics turn out to be extremely similar to the dynamics of the well-known model two sided SYK model introduced by Maldacena and Qi. In particular, we have shown that in the low-temperature regime, the model is gapped, showing then a flat free energy which terminates in a first-order phase transition. We also showed that these physical properties are intimately connected to the chaotic nature of SYK, and they are not present in the non-chaotic version of the model.

Publications:

- G. Cenedese, M. Bondani, A. Andreanov, M. Carrega, G. Benenti, and D. Rosa, *Shallow quantum circuits are robust hunters for quantum many-body scars*, The European Physical Journal Plus 140 (6), 517.
- A Andreanov, M. Carrega, J. Murugan, J. Olle, D. Rosa, and R. Shir, *From Dyson models to many-body quantum chaos*, Physical Review B 111 (3), 035147.
- D. Nemirovsky, R. Shir, D. Rosa, and V. Kagalovsky, *Unsupervised techniques to detect quantum chaos*, Low Temperature Physics 50 (12), 1127-1134.
- T. Čadež, D. K. Nandy, D. Rosa, A. Andreanov, and B. Dietz, *The Rosenzweig–Porter model revisited for the three Wigner–Dyson symmetry classes*, New Journal of Physics 26 (8), 083018.
- T. Čadež, B. Dietz, D. Rosa, A. Andreanov, K. Slevin, and T. Ohtsuki, *Machine learning wave functions to identify fractal phases*, Physical Review B 108 (18), 184202.
- G. Cenedese, M. Bondani, D. Rosa, and G. Benenti,*Generation of pseudo-random quantum states on actual quantum processors*, Entropy 25 (4), 607.
- J. Kim, Y. Oz, and D. Rosa, *Quantum chaos and circuit parameter optimization*, Journal of Statistical Mechanics: Theory and Experiment 2023 (2), 023104.
- J. Wang, B. Dietz, D. Rosa, and G. Benenti, *Entanglement dynamics and classical complexity*, Entropy 25 (1), 97.
- D. Nandy, T. Čadež, B. Dietz, A. Andreanov, and D. Rosa, *Delayed thermalization in the mass-deformed Sachdev-Ye-Kitaev model*, Physical Review B 106 (24), 245147.
- Y. Jia, D. Rosa, J. J. M. Verbaarschot, *Replica symmetry breaking for the integrable two-site Sachdev–Ye–Kitaev model*, Journal of Mathematical Physics 63 (10).
- V. Shaghaghi, V. Singh, G. Benenti, and D. Rosa, *Micromasers as Quantum Batteries*, Quantum Science and Technology 7 (4).
- A. M. García-García, Y. Jia, D. Rosa, and J. J. M Verbaarschot, *Replica symmetry breaking in random non-Hermitian systems*, Physical Review D 105 (12), 126027.
- A. M. García-García, Y. Jia, D. Rosa, and J. J. M Verbaarschot, *Dominance of Replica Off-Diagonal Configurations and Phase Transitions in a PT Symmetric Sachdev-Ye-Kitaev Model*, Physical Review Letters 128 (8), 081601.
- J. Kim, J. Murugan, J. Olle, and D. Rosa, *Operator delocalization in quantum networks*, Physical Review A 105 (1), L010201.
- M. Carrega, J. Kim, and D. Rosa, *Unveiling Operator Growth Using Spin Correlation Functions*, Entropy 23 (2021) 5, 587.

Quantum many-body batteries and quantum thermodynamics In recent days, the possibility of using quantum many-body systems to engineer nano-devices is getting more and more attention. Among several applications, a particularly interesting set of devices is represented by quantum batteries. To make a long story short, a quantum battery is a quantum system that can store energy to be released as physical work at a later stage. The easiest way to achieve this goal is to bring the quantum system, initially prepared in the ground state of a given static Hamiltonian, to an excited state through a quantum quench protocol. The system can then be discharged by bringing it back to a low-energy state. Several figures of merit can be studied to describe the performance of the resulting battery. Among them, two particular figures of merit are the charging power, *i.e.* the speed at which the energy is pumped into the system, and the charging temporal stability, which is the ability of the system to reach a stable value of the energy stored in the battery, thus suppressing the temporal fluctuations.

The team has provided a general theorem on the possibility of getting a quantum advantage in the charging power of a *generic* quantum battery. Our result gives a mathematical proof to a conjecture formulated more than 7 years before and shows that the crucial necessary ingredient to reach such an advantage is represented by *global* unitary operations. As a byproduct of this result, we have provided a new notion of distance between quantum states and a bound on the minimal time required to connect them via a unitary protocol. Another successful line of research which has been pursued is the study of new theoretical models of quantum batteries. More in detail, we have investigated the possibilities of using micromasers as possible models of quantum batteries. We have established the main feature that makes the micromaser a potential quantum battery: the (meta)stable state reached by the electromagnetic field at the end of the charging process is *quasi-pure*. This is an unexpected feature, and it is crucial to make the energy stored in the field usable as a source of work at a later stage. Moreover, we have shown that the charging protocol for the micromaser can be further improved by using AI techniques, that allow it to reach higher levels of stored energy. Remaining in the field of quantum technologies, broadly intended, we have studied the possibilities of unitarily extracting energy from quantum states that are only *partially* known. Given a certain quantum state and a Hamiltonian defining the energy content of the state, one can extract energy from it by doing a unitary evolution bringing the state to a state with lower energy. The problem with such a simple approach is that the choice of the particular unitary is highly dependent on the initial state, which cannot be fully known in most cases. We have considered the realistic situation in which the state is only partially known, *i.e.* that only a restricted set of measurements can be performed. Given this limited information, we developed a theory to determine the unitary operator that *statistically* will extract the maximum amount of work from the state.

Other works include: an analysis of the thermodynamic uncertainty relations in certain variations of maser heat engines, and an analysis of the frictional effects on the asymmetric Otto engine.

Publications:

- V. Singh, V. Shaghaghi, T. Pandit, C. Beetar, G. Benenti, and D. Rosa, *The asymmetric quantum Otto engine: frictional effects on performance bounds and operational modes*, The European Physical Journal Plus 139 (11), 1020.
- J. Gyhm, D. Rosa, and D. Šafránek, *Minimal time required to charge a quantum system*, Physical Review A 109 (2), 022607.
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- D. Šafránek, and D. Rosa, *Measuring energy by measuring any other observable*, Physical Review A 108 (2), 022208.
- D. Šafránek, D. Rosa, and F. Binder, *Work extraction from unknown quantum sources*, Physical Review Letters 130 (21), 210401.
- V. Shaghaghi, V. Singh, M. Carrega, D. Rosa, and G. Benenti, *Lossy micromaser battery: Almost pure states in the Jaynes–Cummings regime*, Entropy 25 (3), 430.

- J. Gyhm, D. Šafránek, and D. Rosa, *Quantum charging advantage cannot be extensive without global operations*, Physical Review Letters 128 (14), 140501.

Perspectives

The team ended its activities in October 2023, when the Team Leader (Dario Rosa) moved to a faculty position at the IFT-Unesp in São Paulo (Brazil).

Cooperations

Within PCS, we collaborated closely with the group "Complex Condensed Matter Systems". International cooperations included quantum chaos in many-body systems (University of Cape Town, South Africa), the SYK model (Stony Brook University, US and Shanghai Jiao Tong University, China), quantum batteries (University of Insubria, Italy), Quantum many-body systems (CNR, Italy), quantum computing (IAS, US and Tel-Aviv University, Israel), quantum batteries and energy extraction (Trinity College, Dublin, Ireland) and quantum chaos and K-complexity (University of Cape Town, South Africa, IFAE, Spain, and Hebrew University, Israel).

1.6.5 Topological and Correlated Quantum Matter

Team Leader: Moon Jip Park

Research Topics

Moire materials. The moiré superlattice of misaligned atomic bilayers paves the way for designing a new class of materials with wide tunability. When two sheets of atomic bilayers are stacked with a finite rotation angle, the periodicity of the two incommensurate layers produces a large moiré superlattice. This giant amplification of the crystalline periodicity is the hallmark of moiré materials and provides a viable platform for band structure engineering. We explore and extend the moiré materials in various correlated electron systems including magnets, intrinsic supercondcutors, transition metal dichalcogenides. We study how the moiré superlattice changes the correlated ground state and induce exotic correlated ground states. We are developing novel numerical techniques to calculate the local order parameters in the presence of the extremely complicated moiré superlattice. Main results:

- *Ab-initio Spin Hamiltonian and Topological Non-centrosymmetric Magnetism in Twisted Bilayer* CrI_3
  Nano Letters 23, 13, 6088–6094 (2023)
- *Replica Higher-Order Topology of Hofstadter Butterflies in Twisted Bilayer Graphene*
  npj Computational Materials, 9, 152 (2023)
- *Controllable magnetic domains in twisted trilayer magnets*
  Phys. Rev. B 108, L100401 (2023)
- *Emergence of stable meron quartets in twisted magnets*
  Nano Letters 24, 1, 74–81 (2024)
- *Stacking-dependent topological electronic structures in honeycomb-kagome heterolayers*
  npj 2D Materials and Applications 9, 57 (2025)

Unconventional correlated materials. The major progress in the field of superconductivity has been sparked by the discovery of new pairing mechanisms. Among various many-body interactions in solid-state matters, the electron-electron Hubbard interaction is the most evidently existing, but simultaneously the most elusive form of interaction for superconductivity. This is because the electron-electron interaction is inadequate to serve as the source of superconducting pairings due to its repulsive nature. However, the confluence of the strong spin-orbit coupling can change the picture. In the presence of the spin-orbit coupling, the Hubbard term is not the only interaction. The multi-orbital feature driven by the spin-orbit coupling can introduce a more complicated form of the electron-electron interaction. So far, the interplay of multiband nature, spin-orbit coupling, and correlation effect have been overlooked. Thus, we plan to develop the systematic theory of the superconductivity with the confluence of the strong spin-orbit coupling. By constructing the microscopic model of the many-body interactions, We clarify how multi-band nature plays a crucial role in the superconductivity of the spin-orbit-coupled materials. In the multi-band systems, the inter-orbital interactions and the Hund's rule couplings are important. Using the Fierz identity and the symmetry analysis, We configure how the complex repulsive interactions exactly transforms as the multi-band particle-hole channels. Main results:

- *Triplet-Superconductivity in Triple-Band Crossings*
  Communications Physics 5, 220 (2022)
- *Hosohedral nodal-line superconductivity in hexagonal ABC Dirac semimetals*
  Communications Physics 7,11 (2024)
- *Collective non-Hermitian skin effect: Point-gap topology and the doublon-holon excitations in non-reciprocal many-body systems*
  Communications Physics 7, 73 (2024)
- *Hierarchical zero- and one-dimensional topological states in symmetry-controllable grain boundary*
  Nature Communications 15:9328 (2024)
- *Unconventional p-wave and finite-momentum superconductivity induced by altermagnetism through the formation of Bogoliubov Fermi surface*
  Phys. Rev. B 111, 054501 (2025)

Topological metamaterials. Topological materials are now being realized in variety of metamaterials including electric circuits, photonic cavities, and nanomechanical systems. The intrinsic non-Hermiticity of these systems exhibits even more complicated phenomena that has no counterparts in the electronic systems. We study various non-Hermiticity induced topological phases in topoelectric circuits and mechanical systems. In addition, we realize the moiré superlattice, using photonic cavity consists of dielectric resonator quasi-atoms characterized by cascades of robust flat bands at large twist angles. Main results:

- *Bloch Theorem Dictated Wave Chaos in Microcavity Crystals*
  Light: Science & Applications 12, 106 (2023)
- *Strong Interlayer Coupling and Stable Topological Flat Bands in Twisted Bilayer Photonic Moiré Superlattices*
  Light: Science & Applications 11, 289 (2022)
- *Length scale formation in the Landau levels of quasicrystals*
  Phys. Rev. B 105, 045146 (2022)
- *Realization of Non-Hermitian Hopf Bundle Matter*
  Communications Physics 6, 273 (2023)
- *Topological Phase Transitions of Generalized Brillouin Zone*
  Communications Physics 7, 21 (2024)
- *Exceptional Classifications of Non-Hermitian Systems*
  Communications Physics 7, 109 (2024)

- *PT-symmetric Non-Hermitian Hopf metal*
  Physical Review Research 6, L012053 (2024)
- *Floquet Chiral Quantum Walk in Quantum Computer*
  Phys. Rev. B 109, L201117 (2024)
- *Quantized polarization and Majorana fermions beyond tenfold classification*
  Communications Physics 7, 243 (2024)
- *Non-Bloch band theory of sub-symmetry-protected topological phases*
  Phys. Rev. B 110, 035424 (2024)
- *Pseudo-Hermitian Topology of Multiband Non-Hermitian Systems*
  Phys. Rev. A 111, 042205 (2025)

Future Perspectives

The division and the team were established in April 2021, with the arrival of Moon Jip Park. Currently, the team consists of three members, Dr. Moon Jip Park (Team leader), Dr. Kyoung Min Kim, Dr. Grigory Bednik. On the team level, we plan to extend the twisted materials to various correlated systems, in particular magnets and superconducting systems. On the division level, we are broadening our spectrum with attractive projects in the field of various metamaterials including nanomechanical systems, photonic crystal, and topoelectric circuits. One of our next goals is to study the quantum geometric effect in flatband systems and controlling electron correlations. This can happen both through consolidating the existing research and establishing a new team.

Collaborations

Within the PCS, we closely collaborate with all junior research teams. In domestic groups, we collaborate with SungBin Lee(KAIST - Studying frustrated magnetism), Myung Joon Han(KAIST - Moire magnets in CrI3), Youngkuk Kim(SungKyunkwan University - Topological nodal superconductivity in ABC materials). Jinwoong Cha(KRISS - Topological nanomechanical systems), and Bumki Min(KAST - Realization of non-hermitian topoelectrical circuits).

International collborations include Jeffrey Teo(University of Virginia - Topological order in coupled wire systems), Youngseok Kim(IBM - quantum simulators in superconducting qubits), Gibaik Sim(Technical university of Munich - Topological superconductivity in triple band crossings), YongBaek Kim(University of Toronto - Superconductivity with Hofstadter butterfly), and Naday Mason (University of Illinois at Urbana-Champaign - Frustrations in superconducting island networks, quantum transport in unconventional superconductivity).

1.6.6 Optics of Quantum Fluids and Nanomaterials
Team Leader: Sergei Koniakhin

Research Topics

Optics of Quantum Fluids and Nanostructures. This team was established as a part of PCS center of IBS on 1 September 2021. Since its establishment, the OQFN team has dedicated itself to investigating the interplay between light and matter at the nanoscale, with particular emphasis on quantum and classical phenomena in emerging materials and nanostructures. The team employs a multidisciplinary approach that combines elements of theoretical condensed matter physics, quantum optics, nanomaterial science, and computational modeling to address fundamental questions and potential applications in next-generation technologies. The main focus of the team is the optical properties of semiconductor nanostructures (supporting existence of exciton-polaritons), artificial optical lattices and nanoparticles.

Various phenomena in the *quantum fluids based on exciton-polaritons* in semiconductor microcavities were studied.

- The pumping intensity threshold for condensation was explicitly related to the polariton spectral line properties and lase pumping size. Fundamental limit on minimal laser power for condensation was established.
  Universal condensation threshold dependence on pump beam size for exciton-polaritons
  Communications Physics 8 (1), 286
- The simulation of time dynamics of steady exciton-polariton condensate by strong impulse was provided to interpret experimental data. The principal role of exciton reservoir in condensate destruction was established
  Exciton reservoir-induced destabilization and reformation of polariton condensate
  Optics Express 33 (8), 18530-18539
- Quantum turbulence studies in realistic lossy exciton-polariton quantum fluid was conducted. Influence of loss rates on incompressible kinetic energy wash shown to be negligible for small loss rates
  Driven-dissipative turbulence in exciton-polariton quantum fluids
  arXiv preprint arXiv:2503.09275 (under review in PRB)
- The effect of an additional quasiresonant drive on the dynamics of the ring-shaped incoherently pumped polariton condensates carrying angular momentum (vorticity) is studied theoretically. Numerical simulations of the 2D and 1D Gross-Pitaevskii equations show that the difference of the topological charges (vorticities) of the condensate and the quasiresonant coherent drive plays a crucial role in the synchronization dynamics.
  Phase locking of ring-shaped exciton-polariton condensates to coherent optical drive
  Physical Review B 112 (8), 085306

In the *artificial photonic lattices*, the gauge fields and topological defects in real and momentum space and their mapping are investigated base on simuating wave packets propagation in a lattice in various configuration. The principal accent was done on the honeycomb lattice.

- The study was devoted to a comprehensive theoretical study of asymmetric (skew) scattering in photonic graphene, with the main focus on its realization with semiconductor microcavity exciton-polaritons and ratchet effect manifestation
  Skew scattering and ratchet effect in photonic graphene
  Physical Review B 110 (20), 205405
- An optical analog of electron snake states was proposed based on an artificial gauge magnetic field in a photonic graphene implemented by varying distances between semiconductor cavity pillars. An intuitive and exhaustive continuous model based on tight-binding approximation was developed and compared with numerical simulations of a realistic photonic structure.
  Optical snake states in a photonic graphene
  Optics Letters 49 (10), 2581-2584
- The regularly distributed quantized vortex arrays in momentum space by probing the honeycomb and hexagonal photonic lattices with a single focused Gaussian beam was observed in experiment with the necessity of theoretical interpretation. It was shown that the resulting spatial patterns of vortices are strongly defined by the symmetry of

the wave packet evolving in the photonic lattices and not by their topological properties
Simultaneous creation of multiple vortex-antivortex pairs in momentum space in photonic lattices
Advanced Photonics 5 (6), 066007

- Perfect Klein transmission in a 2D photonic system (photonic graphene) at normal incidence was experimentally observed and the angular dependence was measured. The theoretical interpretation of the experimental results was given
Angular-dependent Klein tunneling in photonic graphene
Physical Review Letters 129 (23), 233901

Concerning the *optics of nanoparticles*, Raman spectra of crystalline nanoparticles were investigated. The team has developed advanced theoretical models to understand the behavior of optical phonons in confined nanostructures and their manifestation in Raman scattering experiments. This research has significant implications for the characterization of nanomaterials and the interpretation of spectroscopic data

- Theory of optical phonons coupling in paired/intersecting nanoparticles was created with the yield of phonon energy level splitting versus intersection depth
Coupled-oscillator model for hybridized optical phonon modes in contacting nanosize particles and quantum dot molecules
- Physical Review Research 5 (1), 013153
- Theory of optical phonons hybridization in many-particle regular and random ensembles. The relation between the shift and the broadening of the Raman peak and the coupling strength and the disorder is established for nanocrystal solids, agglomerates, and porous media providing the information about the array structure, the structure of its constituents, and the properties of optical phonons.
Localized and extended collective optical phonon modes in regular and random arrays of contacting nanoparticles: Escape from phonon confinement
- Physical Review B 109 (15), 155435
- The research paper was dedicated to investigating how structural disorder and imperfections affect Raman spectra of nanoparticles. Simple relation between broadening and additional red shift and vacancies covventration was given (with linear proportionality to the vacancies concentration)
Raman peak shift and broadening in crystalline nanoparticles with lattice impurities
- Diamond and Related Materials 146, 111182

The following *collaborations* were held during the group run.

A. *Exciton-polaritons, Bose-Einstein condensation, Gross-Pitaevskii equation, Complex Ginzburg-Landau equation*

- KAIST (Prof. Yong-Hoon Cho and Prof. Hyoungsoon Choi)
- Pennsylvania State University (Prof. Igor Aronson)
- ITMO University (Prof. Alexey Yulin)

B. Electromagnetically induced transparency (EIT) effect, graphene, honeycomb lattice, symmetry

- Univ. Clermont Auvergne (Prof. D. Solnyshkov and Prof. G. Malpuech)
- Xi'an Jiaotong Univ. (Prof Zhaoyang Zhang and Prof. Feng Li)

The International Workshop *Exciton-Polaritons in Semiconductor Microstructures and Quantum Optics* was held in the dates April 28 — May 2, 2025. The Workshop allowed extensive communication between Korean scientific community memers and worldwide reknown experts in the field. Many workshop participants has visited KAIST and IBS laboratories for giving talks and providind scientific discussions.

The *future goals* of the group run is continuation of collaboration with KAIST (Prof. Yong-Hoon Cho and Prof. Hyoungsoon Choi) with proposing novel experiments on exciton-polaritons in semiconductor microcavities and interpreting the measured data. On the interst are the topics of many-condensate synchronization, theoretical grounds of exciton-polariton condensation in semiconductor microstructures. Subcritical condensation regime and emission intensity hysteresis with the discussions and research on the possibility of photonic memory effect detection, optical vortex detection.

1.6.7 Superconducting Hybrid Quantum Systems

Team Leader: Sunghun Park

Research Topics

The team studies hybrid quantum systems which are composed of two or more physical components, with the goal of maximizing the advantages and strengths of different systems, to achieve novel quantum technology. The research focuses on developing theoretical models that incorporate physical properties of materials such as spin-orbit coupling, topology, and nanomechanics, proximity coupled to a superconductor and investigating emerging quantum phenomena in such hybrid systems exhibiting novel functionality beyond existing quantum devices. The research topics are as follows.

Nanomechanics in superconducting devices. Nanoelectromechanical systems (NEMS) study nanomechanical degrees of freedom coupled to electron transport. The sequential electron tunneling by the mechanical oscillation of a metallic grain, coined as electron shuttle, was proposed in 1998, offering a noble platform for spatial transportation of electrons. It was naturally followed by its generalization towards coherent transfer of Cooper pairs with a movable superconducting grain. A flying qubit is the building block of a quantum information device for transferring quantum states over a long distance. In this topic, we propose a superconducting system for an oscillating flying qubit by means of nanoelectromechanics combined with Cooper-pair box qubits. We suggest that the flying qubit states can be observed in electron transport to a normal electrode via Andreev reflection.

- *Andreev probing of a Cooper-pair flying qubit*
  Phys. Rev. B 111, 165403 (2025)

Topological quantum matter. Majorana fermions can constitute topological qubits for quantum computation, because their non-abelian statistics allows for topologically protected operations on quantum information. However, in practical platform, boundary of a device hosting Majorana fermions inevitably exists and has to be considered in a theory. We study the effect of the boundary modes on Majorana zero modes in a planar topological Josephson junction, and show that the coupling between the two modes affects the stability of the Majorana zero modes and induces the energy splitting of their states.

- *Boundary-induced Majorana coupling in a planar topological Josephson junction*
  Phys. Rev. B 111, 045414 (2025)

Superconducting diode effect. Superconducting diode effect is a superconducting counterpart of a semiconducting diode and thus has the potential to become a non-dissipative circuit element enabling emergent superconducting technologies. Here, in collaboration with an experimental group, we demonstrate that gate voltages control the unidirectional flow of Cooper pairs via spin-orbit coupling, which allows to create a locally tunable superconducting diode.

- *Electric control of polarity in Josephson diode*
  arXiv:2409.17820 (under review)

Perspectives

For the last three years, I have conducted my research on hybrid quantum systems, with the goal of maximizing the advantages and strengths of different systems, to achieve novel quantum technology. The research focuses on developing theoretical models that incorporate physical properties of materials such as spin-orbit coupling, topology, and nanomechanics, proximity coupled to a superconductor and investigating emerging quantum phenomena in such hybrid systems exhibiting novel functionality beyond existing quantum devices. I have also performed collaboration with Advanced Study Group members as cooperation within the Center and with domestic experimental collaborators, as an independent research group. After allocation of my team with in the trapped-ion center, I plan to expand the spectrum of my research to the trapped-ion system. A collaborative project with the trapped-ion center will be pursued based on common interests in superconducting platform and trapped-ion system. The interests include theoretical models for qubit detection, physical properties of phonons, and the topological characteristics of qubit states.

Cooperations

Strong cooperation inside Korea includes superconducting diode effects (POSTECH, Pohang) and boundary effects on Majorana modes (KIAST, Daejeon). International cooperation includes nanomechanics in superconducting devices (Gothenburg University and Chalmers University of Technology, Sweden) and Andreev states driven by microwaves (UAM, Spain).

1.6.8 Topological Quantum Matter
Team Leader: Dung Xuan Nguyen

Research Topics

The main theme of our research is investigating the interplay between geometry and topology in quantum matters and photonic materials. Our research has the potential to advance our understanding of strongly coupled many-body systems, clarify the role of geometry and gravitational degrees of freedom in condensed matter, and provide insights into the broader concept of emergence in physics.

Geometrical models of Fractional quantum Hall systems. The FQHE, first observed in 1982 and explained by Laughlin's wave function in 1983, revolutionized condensed matter physics by introducing the concept of topological order. In these systems, a two-dimensional electron gas subjected to a strong magnetic field forms highly degenerate Landau levels. When partially filled, electron kinetic energy is quenched, and Coulomb interactions dominate, producing a variety of correlated topological phases. Some phases host non-Abelian anyons, promising candidates for fault-tolerant quantum computation. More broadly, the collective excitations in FQH systems provide a platform for emergent geometric and gravitational dynamics. Whether gravity is emergent remains one of the most fundamental open questions in physics. We plan to address this issue through the study of strongly correlated quantum materials, in particular fractional quantum Hall (FQH) systems where recent experiments have identified chiral spin-2 quasiparticles, candidate emergent gravitons. By analyzing the dynamics of interacting electrons in these systems, we aim to uncover frameworks for non-Einsteinian gravity.

Supersymmetry and supergravity were originally developed in the 1970s as extensions of field theory to address fundamental problems in high-energy physics. While neither has been confirmed in particle physics or cosmology, both frameworks have been crucial to theoretical developments such as superstring theory. Interestingly, strongly correlated condensed matter systems may provide natural settings where supersymmetry can emerge. We propose a supergravity description of the Haldane-Rezayi (HR) state, a gapless FQH phase at half-filling of a Landau level. Within this framework, the edge modes of the HR state and the Girvin-MacDonald-Platzman algebra arise naturally. Exact diagonalization studies further provide evidence for emergent graviton (spin-2) and gravitino (spin-3/2) excitations, suggesting that FQH systems offer an experimental arena for supersymmetric and supergravitational phenomena. Our supergravity model of the HR state predicts both graviton and gravitino excitations and connects naturally to the bimetric theory of FQH states, reproducing the long-wavelength GMP algebra. The corresponding bulk Chern–Simons theory matches the conformal field theory known to describe the HR state. Numerical simulations corroborate these predictions, strengthening the case for emergent gravitational dynamics in FQHE.

The fractional quantum Hall effect thus provides a unique laboratory where condensed matter systems can reveal gravitational and supersymmetric phenomena, suggesting that gravity itself may arise from the quantum dynamics of matter.

Main results:

- *Chiral "Graviton" and Fractional Quantum Hall Effect*
  CHIRAL MATTER: Proceedings of the Nobel Symposium 167, 109-114 (2023)
- *Supergravity model of the Haldane-Rezayi fractional quantum Hall state*
  Phys. Rev. B (12), 125119 (2023)
- *Spin of fractional quantum Hall neutral modes and" missing states" on a sphere*
  Prerpint ArXiv:2503.06914 (2025)

Effective descriptions of superfluid systems. Vortices are topological solutions of the Gross-Pitaevskii equation, carrying quantized circulation due to the quantum nature of the superconducting phase. In rotating superfluids, vortices naturally arrange into a triangular lattice as the ground state. Despite decades of research, recent progress has enabled a modern field-theoretic approach to vortex lattices. In the rotating frame, the Coriolis force mimics the Lorentz force, giving atoms an effective magnetic field proportional to their mass and angular velocity. In the lowest Landau level (LLL) limit, reached at high rotation speeds, the state of the superfluid is fully determined by the vortex positions. The lattice in this regime becomes incompressible due to emergent LLL symmetry, leaving only one low-energy excitation: the transverse phonon mode, known as the Tkachenko mode. This mode acts as the Nambu–Goldstone boson of both magnetic translation symmetry and particle-number conservation. Using emergent symmetries, one can construct a consistent nonlinear theory of vortex lattices, opening new ways to analyze their low-energy dynamics. However, several open questions remain regarding their behavior in the LLL limit.

Related phenomena arise in bilayer fractional quantum Hall (FQH) systems, where interlayer excitons can undergo Bose–Einstein condensation, giving rise to a superfluid phase. In these systems, electrons in a quantum Hall fluid bind with vortices to form composite fermions or composite bosons. A bilayer quantum Hall state at certain filling factors and interlayer separations can be described in terms of these composite particles. At small separations, the system resembles excitons formed from paired electrons and holes, while at larger separations it is better described by excitons of paired composite fermions, with each electron binding to four vortices. Overlap calculations with exact diagonalization show that the number of vortices bound to electrons increases with layer separation. Trial states for Goldstone and meron excitations further capture the essential low-energy physics, highlighting deep connections between vortex matter in superfluids and excitonic condensates in quantum Hall bilayers.

Main results:

- *Noncommutative field theory of the Tkachenko mode: Symmetries and decay rate*
  Phys Rev. Res. 6 (1), L012040 (2024)
- *Successive electron-vortex binding in quantum Hall bilayers at* $\nu = 1/4 + 3/4$
  Phys. Rev. B 110 (19), 195106 (2024)
- *On quantum melting of superfluid vortex crystals: From Lifshitz scalar to dual gravity*
  Sci Post Phys 17 (6), 164 (2024)

Topological photonic crystals. Photonic crystals lie at the forefront of physics, materials science, and engineering, offering unprecedented control over the behavior of light. These structures, designed with periodic variations in dielectric properties on a length scale comparable to the wavelength of light, provide a powerful platform for manipulating photon propagation. The central principle is the formation of photonic band gaps—frequency ranges where light cannot propagate—closely analogous to electronic band gaps in semiconductors. This capability enables fine tuning of optical properties and drives advances across diverse technological applications. In recent years, photonic crystals have also become a fertile setting for exploring topological physics. By incorporating topological concepts into their design, researchers have uncovered striking optical phenomena such as edge states and protected modes. This fusion of photonics and topology extends condensed matter ideas into the optical domain, while simultaneously opening new avenues for robust and innovative photonic devices.Our work advances this direction by developing and refining the theoretical framework for multilayer photonic crystals. In collaboration with colleagues, we derived an effective field theory description of their photonic band structures and investigated the emergence of nontrivial topological features, including non-Hermitian effects, in such systems.

Main results:

- *Fermi arc reconstruction in synthetic photonic lattice*
  Phys. Rev. Lett. 131 (5), 053602 (2023)
- *Reconfigurable topological lasing through Thouless pumping in bilayer photonic crystal*
  Prerpint ArXiv:2111.02843 (2025)
- *Berry Monopole Scattering in the Synthetic Momentum Space of a Bilayer Photonic Crystal Slab*
  Prerpint ArXiv:2507.11983 (2025)
- *Generalized Guided Mode Expansion for Non-Hermitian Resonances in Photonic Crystal Slabs*
  Prerpint ArXiv:2507.20033 (2025)

Emergent gauge theories in lattices models. Gauge theory in lattice models uncovers rich mechanisms of confinement, condensation, and topological order. In the deformed toric code, the transition from a topological to a trivial phase displays an unconventional confinement: magnetic charges are confined yet can still be displaced without energy cost by non-unitary operators that reduce the state's norm. This phenomenon reflects the persistence of the toric code's ground-state degeneracy across the transition, explained through spontaneous breaking of generalized 1-form symmetries. Such coexistence of higher-form symmetry breaking with a trivial phase emphasizes subtle constraints in relating topological phases to symmetry breaking.

In higher dimensions, lattice gauge theories reveal even more exotic excitations. (3+1)-dimensional topological phases host both point-like and loop-like excitations, with braiding processes not possible in lower dimensions. Linked loops exhibit three-loop braiding, where two loops exchange while tied to a third. A Hamiltonian realization of Dijkgraaf–Witten theory with finite Abelian groups and 4-cocycle twists allows explicit construction of membrane operators, which define fusion and braiding rules, measure topological charges, and confirm that charges on a 2-torus match the ground-state degeneracy on a 3-torus. These insights show how lattice gauge theories naturally capture higher-form symmetries, unconventional confinement, and exotic braiding central to modern quantum matter.

Main results:

- *Gaining insights on anyon condensation and 1-form symmetry breaking across a topological phase transition in a deformed toric code model*
  SciPost. Phys. 15 (6), 253 (2023)

- *Twisted lattice gauge theory: Membrane operators, three-loop braiding, and topological charge*
  Phys. Rev. B 110 (3), 035117 (2024)

More. Various other research activities enrich and cross-fertilize the work of the team. These include strained graphene, chaos, among others.

Main results:

- *Flux-induced midgap states between strain-engineered flat bands*
  Phys. Rev. B 108 (11), 115148 (2023)

- *Haldane graphene billiards versus relativistic neutrino billiards*
  Phys. Rev. B 110 (9), 094305 (2024)

Perspectives

The team was established in 2023 under the leadership of Dung Xuan Nguyen. Over the past three years, we have conducted research across several of the topics listed above, resulting in 15 papers, including both publications and preprints. Looking ahead, we aim to collaborate with leading international experts in topological quantum matter and photonic materials to deepen our understanding of the quantum world and to explore potential technological applications arising from our interdisciplinary research.

Cooperations

Within the PCS, we collaborate closely with the group "Complex Condensed Matter Systems".

International cooperations include Quantum phase transitions in superfluids (Karlstad University, Sweden;Niigata University, Japan), fractional quantum Hall (University of Chicago, US ; Raman Institute, India; Princeton University, US; Florida State University, US), generalized symmetries (University of Toronto, Canada), topological photonics (Lyon Institute of Nanotechnology, France;Donostia International Physics Center, Spain; ASTAR, Singapore), fractional Chern insulators (Nanyang Technological University, Singapore; The University of Hong Kong, China), strained graphene (Lancaster University, U).

1.6.9 Quantum Thermodynamics and Information Theory
Team Leader: Dominik Šafránek

Research Topics

Quantum Work Extraction

Efficient energy extraction is a key quest for living beings and modern technology alike. In recent years the advent of quantum technology has spurred the study of energy sources beyond the classical realm and the emerging field of quantum thermodynamics has investigated the role of quantum features in this task. At the same time while modern quantum technology already finds applications in secure communication, sensing, and computing, these devices need to be powered, conceivably with nonequilibrium, quantum sources of energy. Generally, if one wants to make use of energy from an energy source, the first step is to characterize it. In the quantum regime, the energetic potential of the source is given by the quantum state it produces and measured by the Hamiltonian. Energy can be extracted by performing operations that transform this state into a state of lower energy, and collecting the surplus in the process.

In this direction, we derived a new notion of ergotropy applicable when nothing is known about the quantum states produced by the source, apart from what can be learned by performing only a single type of coarse-grained measurement. This notion of ergotropy represents a realistic measure of extractable work, which can be used as the relevant figure of merit to characterize a quantum battery.

- *Work extraction from unknown quantum sources*
  Phys. Rev. Lett. 130, 210401 (2023)

Second, in order to extract work, one has to be able to determine how much available energy there is. If, for example, the quantum state contains a small amount of energy then the work extraction protocol may cost more than is extracted. Thus, we developed a method to estimate how much energy a quantum state contains, with any, even limited, measurement.

- *Measuring energy by measuring any other observable*
  Phys. Rev. A 108, 022208 (2023)

Quantum Batteries

In recent years tremendous efforts have been devoted to developing quantum technologies, which are now coming to fruition in several fields of practical use. Among the largest successes is quantum metrology, which led to the detection of gravitational waves, quantum cryptography, which finds applications in communicating sensitive data [4,5], quantum computing, which promises to revolutionize chemistry as well as to speed up or solve important problems in optimization, cybersecurity and data analysis, and nanoscale thermodynamic devices, which offer unprecedented precision in thermometry. At large, society is moving toward quantum technologies, because they promise to offer faster, smaller, and more precise devices.

All of these achievements require an efficient way of storing and using energy, as well as fast charging and discharging. The necessity of charging and discharging goes well beyond the quantum world. Examples are electric vehicles where the charging time is one of the main bottlenecks in preventing the widespread use of such technology, or future fusion power plants, in which a large amount of energy needs to be pumped in a short amount of time and discharged in an instant to start the reaction. In the quantum world, nanoscale devices will require nanoscale batteries, with no energy to spare.

In our group, we proved a long-standing conjecture on the limit of charging speed of the quantum battery. We showed, that unlike in a classical battery, where charging speed remains independent of the number of cells, in quantum battery the speed scales at most linearly.

- *Quantum charging advantage cannot be extensive without global operations*
  Phys. Rev. Lett. 128, 140501 (2023)

Taking this research further, we investigated what is the maximal charging speed for a given state. We found that this is given by the Bures Angle for pure states, while for mixed states this defines a metric with very interesting mathematical properties, such as discontinuity when the rank of the state changes.

- *Minimal time required to charge a quantum system*
  Phys. Rev. A 109, 022607 (2024)

Quantum Information and Entropy

Quantum Information is the theoretical backbone of quantum technologies. In this regard, entropy is an important concept: both as informational concept — measuring communication channel capacity — and thermodynamic concept — measuring the amount of disorder in a system. In this line of research, our team investigated several aspects of a type of observer-dependent entropy called observational entropy.

First, we generalized this concept to include completely general measurements, that correspond to any physical measurement an observer can do. We also showed that this is connected to the theory of prediction and retrodiction, giving an interesting alternative interpretation to this quantity.

- *Quantifying information extraction using generalized quantum measurements*
  Phys. Rev. A 108, 032413 (2023)
- *Observational entropy, coarse-grained states, and the Petz recovery map: information-theoretic properties and bounds*
  New J. Phys. 25, 053002 (2023)

Then we investigated differences between informational values of different measurements, some of which were defined by observational entropy.

- *Entropic partial orderings of quantum measurements*
  Phys. Scr. 100, 015298 (2024)

Finally, we generalized the concept of observational entropy to include general quantum priors, which are the assumptions of the observer on the measured state. In more detail, we demonstrate two interpretations of observational entropy, one as the statistical deficiency resulting from a measurement, the other as the difficulty of inferring the input state from the measurement statistics by quantum Bayesian retrodiction. These interpretations show that the observational entropy implicitly includes a uniform reference prior.

- *Observational entropy with general quantum priors*
  Quantum 8, 1524 (2024)

Perspectives

The team research consolidated during the report period around the main themes listed above. We plan to extend the activities to include diagnostic methods for quantum technologies, such as quantum tomography, and to study Kolmogorov-Sinai entropy in quantum systems. Finally, we plan to implement the work extraction protocol on the IBM quantum computer.

Cooperations

Within the PCS, we collaborate with all junior research teams. Strong cooperations inside Korea is on quantum batteries, Lie algebras and Gaussian states (SNU, Seoul).

International cooperations include entropy (University Autonoma, Barcelona, Spain, Nagoya University, Japan), retrodiction (National University of Singapore), chaos and quantum thermodynamics (University of Science and Technology, Singapore).

Chapter 2

Selection of Research Results

Contents

2.1 Prethermalization in Proximity to Integrability

Sergej Flach

Conceptually, the notion of thermalization in closed many-body Hamiltonian systems is well defined for classical systems, in contrast to quantum ones. The most reasonable way to quantify thermalization is to measure the time scales over which a time-averaged observable becomes independent of the system's initial state, up to a prescribed tolerance.

Ergodization time scales can be obtained from time-averaged observable fluctuations (ergodicity), while mixing or Lyapunov time scales can be derived from the inverse of the computed Lyapunov spectra. Lyapunov spectra are universal in the sense that they are invariant under coordinate transformations, and are therefore our preferred tool of analysis. Each integral of motion enforces a pair of Lyapunov exponents to vanish.

Lyapunov exponents appear in ± pairs; in what follows, we consider only the irreducible nonnegative part. We order the exponents as $\Lambda_1 > \Lambda_2 > \cdots > \Lambda_N$, where N is the number of degrees of freedom in our computations, and at least $\Lambda_N = 0$ due to energy conservation. We characterize the spectrum conveniently by Λ_1 and the rescaled spectrum $\bar{\Lambda}(\rho)$ with $\rho = i/N$. The rescaled Kolmogorov–Sinai (KS) entropy,

$$\kappa = \int_0^1 \bar{\Lambda}(\rho)\, d\rho,$$

serves as a useful integral measure of the rescaled spectrum.

Prethermalization. What, then, is prethermalization? Assume that our Hamiltonian depends on one or more tunable parameters, while conserving energy and possibly several other integrals of motion, a total of $P \geq 1$. As we vary these parameters, we may observe that a time-averaged observable appears to converge at some apparent time T_1, yet its value still depends on the initial state. This defines an intermediate regime. At a later time T_2, the observable departs from this transient plateau and eventually converges to a final asymptotic value that is independent of the initial state. If the interval $T_2 - T_1$ diverges as the parameter approaches a limiting value, the phenomenon qualifies as *prethermalization*.

Prethermalization may arise when the limiting parameter restores one or more additional ($Q \geq 1$) integrals of motion on top of the existing P. If the total number $P+Q$ remains finite, a macroscopic system will still exhibit chaos and a macroscopic number of nonzero Lyapunov exponents. In this regime, the emerging Q integrals of motion fluctuate slowly in time and are often referred to as *adiabatic invariants*.

A more extreme case occurs when the limiting parameter restores all possible integrals of motion, rendering the Hamiltonian integrable. In the vicinity of integrability, the Lyapunov spectrum collapses to zero. The largest Lyapunov exponent typically vanishes algebraically with the parameter variation. The scaling of the spectrum may follow one of two scenarios: (i) a *long-range network* regime, where the rescaled KS entropy κ remains finite and nonzero at the integrable limit, or (ii) a *short-range network* regime, characterized by an exponential suppression of the spectrum relative to the largest Lyapunov exponent [1], resulting in a vanishing κ at the integrable limit [2, 3].

Special Initial States - FPUT and Long Range Networks The long-range network scenario is realized in a Fermi–Pasta–Ulam–Tsingou (FPUT) chain in the limit of weak nonlinearities or low energy densities. In this case, prethermalization emerges due to special initial conditions—most notably the classical FPUT condition, where only a single mode (typically the lowest-frequency one) is initially excited [4]. The excited mode resonantly couples to a few low-frequency modes but fails to excite nonresonant higher modes, producing a nonequipartitioned state that persists for a potentially large and even diverging time T_2. During this stage, the

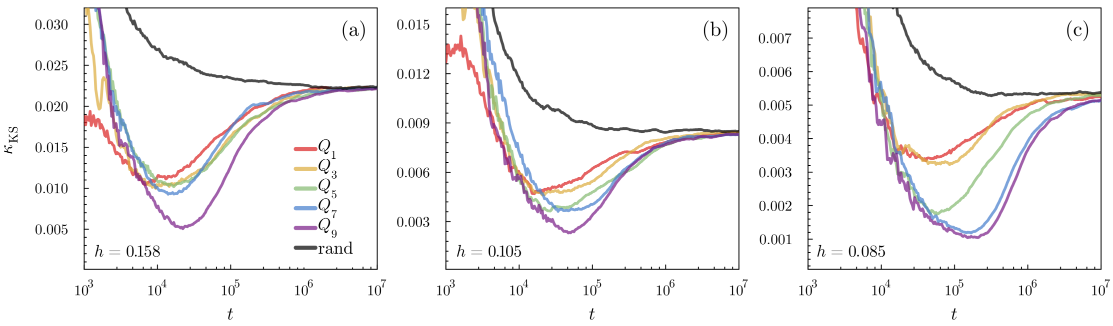

Figure 1: Time-dependent Kolmogorov–Sinai entropy in an α-FPUT chain with N=63 and α=1/4, computed from roots (colored lines) and from a random state (black). Each panel corresponds to an initial state with decreasing energy density h, indicated in the upper left corner [6].

dynamics among the resonant low-frequency modes remain chaotic, with a Lyapunov time (the inverse of Λ_1) much shorter than T_2. As shown in Ref. [6], prethermalization manifests as an anomaly in the temporal evolution of the rescaled KS entropy, which dips below its asymptotic value for extended intermediate times. The duration of this dip increases both as the energy density decreases and as the frequency of the initially excited mode increases, as illustrated in Fig. 1.

Generic Initial States - Short Range Networks Short-range network behavior can be realized in systems where the nearest-neighbor coupling tends to zero [1–3], or by introducing disorder [5]. In such cases, thermalization slows down due to rare chaotic resonances that are spatially separated by increasing distances as the system approaches the integrable limit, while their strength simultaneously diminishes. Measurements of the largest Lyapunov exponent Λ_1 then exhibit increasingly long time intervals where the seemingly converged value depends on the initial condition. Only for sufficiently long evolution times do all trajectories converge to a unique value, as demonstrated in Ref. [7], see Fig. 2.

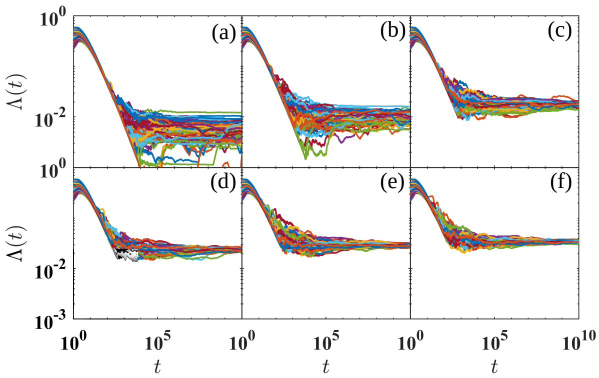

Figure 2: Time evolution of the largest Lyapunov exponent $\Lambda(t)$ up to 10^{10} for different values of the coupling constant θ in the short-range network (SRN) case with $g = 1$, within the unitary circuits map [7]. Panels (a)–(f) correspond to $\theta = 0.001, 0.002, 0.004, 0.006, 0.008$, and 0.01, respectively. Each panel shows 100 trajectories obtained from different initial conditions, displaying $\Lambda_1(t)$ on a $\log_{10}$ scale. The system consists of $N = 50$ unit cells.

[1] Merab Malishava and Sergej Flach, *Phys. Rev. Lett.*, **128** 134102, (2022).

[2] Merab Malishava and Sergej Flach, *Chaos*, **32** 063113 (2022).

[3] Gabriel M Lando and Sergej Flach, *Physical Review E* **108** L062301 (2023).

[4] E Fermi, J Pasta, and S Ulam, Studies of the nonlinear problems, i. Los Alamos Report LA-1940, 1955. later published in Collected Papers of Enrico Fermi, ed. E. Segre, vol. ii, 1965.

[5] Weihua Zhang, Gabriel M Lando, Barbara Dietz, and Sergej Flach, *Physical Review Research* **6** L012064 (2024).

[6] G. M. Lando and S. Flach, *Physical Review E* **112** 014206 (2025).

[7] Xiaodong Zhang, Gabriel M Lando, Barbara Dietz, and Sergej Flach, *Low Temp. Phys.* **51** 870 (2025).

2.2 Trotter transition in BCS pairing dynamics

A. Patra, E. A. Yuzbashyan, B. L. Altshuler, S. Flach

Introduction and Motivation: We investigate how time discretization — via Trotterization or equivalently symplectic integrators — affects the dynamics of the integrable reduced BCS model [1]. In both classical computation and digital quantum simulation, complex Hamiltonians are approximated by splitting them into solvable pieces, evolving under each, and recombining. While exact in the continuum limit, finite step sizes can generate artificial dynamics, sometimes chaotic. Earlier studies showed that symplectic integration can induce chaos in integrable systems like the Toda chain. Here, the authors extend this line to the mean-field reduced BCS Hamiltonian, a compact system of classical spins representing Anderson pseudospins.

The central discovery is a Trotter transition: as the Trotter step τ grows, the system undergoes a dynamical shift from weak chaos (perturbed integrability) to strong, memoryless chaos. This transition parallels quantum chaos observed in digital simulations and shares features with paradigmatic chaotic systems like the kicked top.

The Reduced BCS Model and Trotterization: The reduced BCS Hamiltonian,

$$\hat{H}_{\mathrm{BCS}} = \sum_{j=1}^{N} \varepsilon_j (\hat{c}^\dagger_{j\uparrow}\hat{c}_{j\uparrow} + \hat{c}^\dagger_{j\downarrow}\hat{c}_{j\downarrow}) - g \sum_{j,q=1}^{N} \hat{c}^\dagger_{j\uparrow}\hat{c}^\dagger_{j\downarrow}\hat{c}_{q\downarrow}\hat{c}_{q\uparrow}, \tag{1}$$

describes Cooper pairing between time-reversed states. Using Anderson pseudospins, the model maps to a system of N classical spins under mean-field approximation. In the thermodynamic limit, both the quantum and mean-field forms are integrable.

To implement symplectic integration, the Hamiltonian is split into two parts:

$$H_{\mathrm{BCS}} = \underbrace{\sum_{j=1}^{N} 2\varepsilon_j S_j^z}_{H_{\mathrm{free}}} \underbrace{-g \sum_{j,k=1}^{N} S_j^+ S_k^-}_{H_{\mathrm{int}}} \equiv H_{\mathrm{free}} + H_{\mathrm{int}}. \tag{2}$$

with each piece exactly solvable as rotations of spins. The SABA2 integrator — which is second order with a precision of $\mathcal{O}(\tau^3)$ in the single-step time evolution operator $e^{\tau L}$, where τ is the step size and L is the Liouvillian operator — is employed to evolve the system, mimicking Suzuki-Trotter decompositions in quantum simulation.

Diagnostic Tools — Lyapunov Spectra and Entropy: Chaos is quantified via Lyapunov characteristic exponents (LCEs). These measure exponential growth rates of infinitesimal deviations, obtained from the variational equations of motion. The Lyapunov spectrum encodes the full set of exponents, while the maximum Lyapunov exponent (mLCE) Λ_1 signals chaos if positive. Another diagnostic is the Kolmogorov–Sinai (KS) entropy, the sum of positive exponents per degree of freedom, which quantifies information production.

The analysis reveals distinct scaling behaviors for Λ_1 with τ — See Fig. 1:

- *Small τ (near integrability):* We have $\Lambda_1 \propto \tau^\eta$ where $\eta = 1.40 \pm 0.06$ for $N = 32$ and $\eta = 1.29 \pm 0.09$ for $N = 64$. Weak chaos emerges due to long-range coupling between action variables (long-range network class).
- *Large τ (memoryless chaos):* In the memoryless regime, we obtain $\eta = -0.85 \pm 0.02$ both for $N = 32$ and $N = 64$. Dynamics become strongly chaotic with short temporal correlations, akin to ergodic random maps.

The rescaled Kolmogorov-Sinai entropy mirrors this transition: saturating at finite values in the weakly chaotic regime, but dropping sharply in the memoryless regime.

Analytical Insights and Connection to the Kicked Top: A remarkable feature is that in the large τ regime, the dynamics map onto the well-studied kicked top. For $N = 2$ with particle-hole symmetry, the SABA2 map reduces to iterations of a kicked top Hamiltonian.

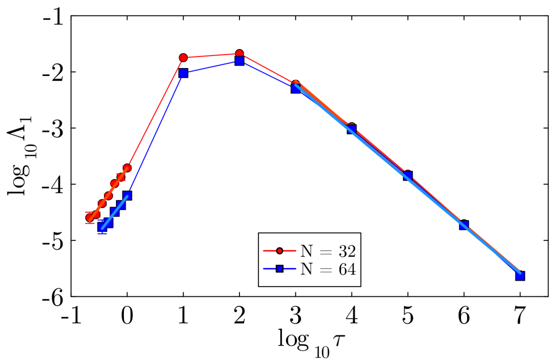

Figure 1: We show $\log_{10}\Lambda_1$ as a function of $\log_{10}\tau$ for $N = 32$ and 64. We have included the error bars. For a fixed N, we choose a configuration where all the spins point in random directions. In the memoryless regime, the N dependence of Λ_1 is quite weak.

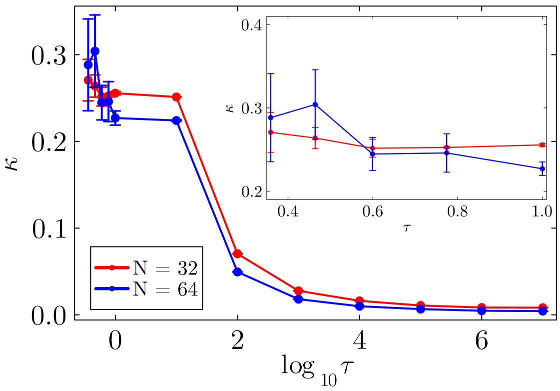

Figure 2: We show the rescaled Kolmogorov-Sinai entropy κ as a function of $\log_{10}\tau$ for $N = 32$ and 64. In the inset, we show a magnified κ versus τ plot for the small τ long-range network regime.

This allows an analytical scaling law:

$$\tau\Lambda_1 \approx 2\ln\left(\tau/\sqrt{N}\right) + C_N, \tag{3}$$

where C_N is a τ independent constant. This is valid only when $\tau/\sqrt{N} \gg 1$. This explains the observed universal scaling and weak N-dependence in the chaotic regime. From this, the critical step size for the transition is estimated as $\tau_c \sim \sqrt{N}$, in excellent agreement with numerics.

Conclusion and Broader Implications: This paper demonstrates that time discretization itself can induce chaos in an integrable many-body model, leading to a Trotter transition governed by universal scaling. The reduced BCS model provides a clean, compact phase-space setting where both weak and strong chaos can be systematically analyzed. The interplay between symplectic integrators, Lyapunov spectra, and mapping to the kicked top reveals deep connections between numerical methods, classical chaos, and quantum simulation. These insights are not only of theoretical importance but also crucial for understanding the reliability of digital quantum simulators and classical integrators in many-body physics.

For digital quantum computers, Trotter errors and chaotic instabilities may follow similar scaling laws. The reduced BCS model's all-to-all interactions make it relevant for near-term quantum devices with global connectivity. Future directions include studying disorder, noise, and different integrators, as well as exploring nonlocal observables such as entanglement entropy and the Loschmidt echo, where mean-field theory breaks down.

[1] A. Patra, E. Yuzbashyan, B. Altshuler, and S. Flach, Trotter transition in BCS pairing dynamics, arXiv:2506.08657.

2.3 Machine learning wave functions to identify fractal phases

Tilen Čadež, Barbara Dietz, Dario Rosa, Alexei Andreanov, Keith Slevin, Tomi Ohtsuki

We demonstrate that an image recognition algorithm based on a convolutional neural network provides a powerful procedure to differentiate between ergodic, non-ergodic extended (fractal) and localized phases in various systems: single-particle models, including random-matrix and random-graph models, and many-body quantum systems [1]. We propose an efficient procedure in which the network is successfully trained on a small data set of only 500 wave functions (images) per class for a single model which exhibits these phases. The trained network is then used to classify phases in the other models. We discuss the strengths and limitations of the approach.

Convolutional neural networks are networks which take a certain input in the form of a single or multiple arrays, process it and produce an output, based on the task to be fulfilled. In the case of image recognition the CNN takes an image as an input and as an output classifies the content of the image. A famous example is the handwritten digit recognition, where the task is to correctly recognize handwritten digits. Here we use the CNN to recognize different phases of matter, specifically the ergodic extended phase, the non-ergodic extended (fractal) phase and a localized phase in various systems.

To obtain the eigenfunctions we use the exact diagonalization by solving the equation $H|\psi_\mu\rangle = \varepsilon_\mu|\psi_\mu\rangle$, which is written as $|\psi_\mu\rangle = \sum_i \psi_\mu(i)|i\rangle$, where $\psi_\mu(i)$ are the coefficients of the μ-th eigenfunction in the basis $|i\rangle$. The input data given to the CNN are the squares of the absolute value of the eigenstate coefficients $|\psi_\mu(i)|^2$. The output classes of the CNN are the probabilities that an eigenfunction belongs to the ergodic (E), fractal (F) and localized (L) states, respectively. We consider a set of models that exhibit a transition from extended to localized phases, in some cases via an intermediate fractal phase.

To train and test the CNN we use the eigenstates of the generalized Rosenzweig-Porter model (gRP), which comprises Hermitian random matrices whose elements are Gaussian distributed with zero mean. The variances of the diagonal and off-diagonal elements, denoted by σ_d^2 and σ_{off}^2, respectively, are defined as

$$\sigma_d^2 = \langle H_{nn}^2 \rangle = \frac{1}{2N}, \quad \sigma_{off}^2 = \langle H_{nm}^2 \rangle = \frac{1}{4\,N^{\gamma+1}}. \tag{1}$$

Here, the parameter γ determines the strength of the off-diagonal matrix elements compared to that of the diagonal ones. In this work we consider real matrices so that at $\gamma = 0$ they are members of the Gaussian orthogonal ensemble (GOE). It was shown that the states around the band center exhibit three distinct phases: an ergodic phase for $\gamma < 1$, an extended non-ergodic phase for $1 < \gamma < 2$ and a localized phase for $\gamma > 2$. The phase diagram was confirmed and the properties of the model were further studied recently.

We use the three distinct phases of the gRP model as the output classes of the CNN. For training the CNN we use the eigenstates obtained from diagonalizing the gRP model. We use $N \times N$ matrices with $N = 2048$ and provide the absolute-value square of the eigenstate coefficients to the input layer. For each of the three phases we extract a single eigenstate corresponding to the eigenenergy closest to the band center, $E = 0$, for in total 3×500 (ergodic, fractal, localized) random-matrix realizations and use them as input training data set. The 90% of the input data is used as a training set and the remaining 10% as the validation set. The output layer classifies the ergodic, fractal, and localized phases in terms of probabilities for each phase.

The network architecture consists of two convolutional layers, each followed by a pooling layer where we utilize a max pooling strategy. We flatten the data and apply a dense layer af-

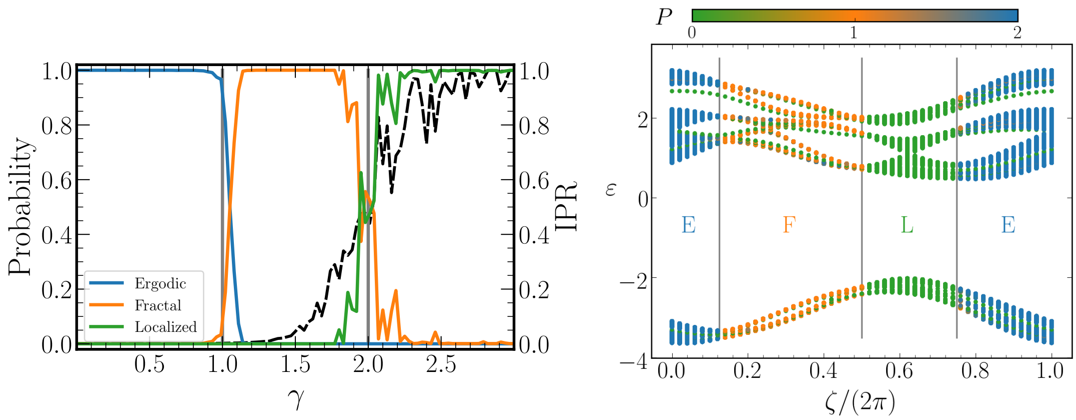

Figure 1: Left: Testing the trained CNN on the gRP model. The probabilities of each of the phases as well as the average IPR (black dashed line) are shown. The gray vertical lines indicate the analytical values γ_E and γ_L for the ergodic and Anderson transitions. Right: A simple function of the probabilities associated with the different phases obtained from the CNN, $P = 0 \cdot P_L + 1 \cdot P_F + 2 \cdot P_E$, where P_L, P_F, P_E are the probabilities for localized (L), fractal (F) and ergodic (E) phases, respectively. Gray vertical lines mark the exact transition values.

ter the second pooling layer, followed by a rectified linear unit (ReLU) activation function. Finally a second dense layer is applied followed by a softmax activation. We use the categorical crossentropy between the output probabilities as a loss function during the training for each of the three phases and the corresponding labels.

After the training, we test the CNN on a new set of gRP eigenstates: The resulting probabilities for the three phases are shown in Fig. 1. The CNN successfully recognizes each of the phases with probability close to 1. For both the phase transitions, the precision of the determination of the critical value of γ is about 10%. For comparison, we also plot the average IPR.

For the extended Harper's model (eH) with the modulated onsite potential V_n and modulated nearest neighbor hoppings t_n,

$$H\psi_n = V_n\psi_n + t_n\psi_{n+1} + t^*_{n-1}\psi_{n-1}, \tag{2}$$
$$V_n = 2\,\cos(2\pi\alpha n + \varphi)$$
$$t_n = \lambda_1\, e^{-2i\pi\alpha(n+1/2)-i\varphi} + \lambda_2 + \lambda_3\, e^{2i\pi\alpha(n+1/2)+i\varphi}$$

the phase diagram is established analytically. We choose $\alpha = (\sqrt{5}-1)/2$ and $\varphi = 0$.

We consider a closed loop parameterized the angle ζ in the two parameter space λ_1, λ_2, which transverses all the three distinct phases of the model

$$\lambda_1 = 0.5 + r_0 \sin(\zeta),$$
$$\lambda_2 = 1.0 + 2r_0 \cos(\zeta). \tag{3}$$

We set $r_0 = 1/4$ and increased ζ from 0 to 2π in steps of 0.02π. For each point on the loop, we test the CNN on *the full spectrum* of eigenfunctions. The results are presented in Fig. 1. The CNN recognizes the ergodic and localized phases with probabilities close to 1 for the majority of the states and correctly identifies about 85% of the fractal states. The transition regions are sharp. Similar results were observed for other models.

[1] Tilen Čadež, Barbara Dietz, Dario Rosa, Alexei Andreanov, Keith Slevin, Tomi Ohtsuki, Phys. Rev. B 108, 184202 (2023).

2.4 Enhancement of Superconductivity in the Fibonacci Chain

Meng Sun, Tilen Čadež, Igor Yurkevich, Alexei Andreanov

We study the interplay between quasiperiodic disorder and superconductivity in a one-dimensional tight-binding model with the quasiperiodic modulation of on-site energies that follow the Fibonacci rule, and all the eigenstates are multifractal [1]. As a signature of multifractality, we observe the power-law dependence of the correlation between different single-particle eigenstates as a function of their energy difference. We numerically compute the mean-field superconducting transition temperature for every realization of a Fibonacci chain of a given size and find the distribution of critical temperatures and analyze their statistics. We find an enhancement of the critical temperature compared to the analytical results that are based on strong assumptions of the absence of correlations and self-averaging of multiple characteristics of the system, which are not justified for the Fibonacci chain. For the very weak coupling regime, we observe a crossover where the self-averaging of the critical temperature breaks down completely and strong sample-to-sample fluctuations emerge.

We consider the 1D Fibonacci chain – a fundamental model representing quasicrystals – with on-site energies arranged according to the Fibonacci rule:

$$\hat{H}_F = -\sum_i \left(\hat{c}_i^\dagger \hat{c}_{i+1} + \hat{c}_{i+1}^\dagger \hat{c}_i + h_i \hat{c}_i^\dagger \hat{c}_i\right) , \quad (1)$$

The potential h_i takes two values $\pm h$ which are arranged according to the Fibonacci sequence rule $\mathcal{F} : \{A \to AB\,, B \to A\}$. The nth Fibonacci sequence S_n is the concatenation of the two previous ones $S_n = [S_{n-1}, S_{n-2}]$. For a system of size L, we first write down a long enough Fibonacci sequence, then cut a segment containing L consecutive letters, and make the substitution $A \to h$ and $B \to -h$. This way, we generate $N = L/2$ ($N = ((L-1)/2)$ for L even (odd) number of different realizations of Fibonacci potential. This chain exhibits several noteworthy properties: (i) construction following a well-defined deterministic algorithm; (ii) the Fibonacci chain possesses a finite number of possible configurations allowing detailed analysis; (iii) all eigenstates exhibit multifractal behavior for all strengths of the onsite potential h leading to intricate patterns with varying degrees of complexity and self-similarity.

The most important property of multifractal systems for the superconducting transition, is the energy resolved overlap of different eigenstates,

$$C(\omega) = L^d \sum_{\mathbf{r},n,m} \langle |\psi_n(\mathbf{r})|^2 |\psi_m(\mathbf{r})|^2 \delta\left(\epsilon_m - \epsilon_n - \omega\right)\rangle , \quad (2)$$

where L^d is the system volume, $\psi_n(\mathbf{r})$, ϵ_n are the eigenstate and eigenenergy of the Hamiltonian (1) and ω is the fixed energy difference between two eigenstates, respectively. This function demonstrates power-law decay at the Anderson transition

$$C(\omega) = \left(\frac{E_0}{|\omega|}\right)^\gamma , \quad (3)$$

in some frequency domain $\delta_L < \omega < E_0$, where δ_L is the mean level spacing, E_0 is the energy scale, and γ is connected to the multifractal dimension. We confirm the power-law decay of the correlation in the Fibonacci chain, see Fig. 1, for different disorder strengths, by numerical diagonalization of the Hamiltonian (1) and averaging over different realizations.

The spinful fermions on a tight-binding chain with local attraction are described by the negative-U Hubbard Hamiltonian,

$$\hat{H} = \sum_\sigma \hat{H}_{F,\sigma} + U \sum_{i=1}^{L} \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$

where the single-particle part $\hat{H}_{F,\sigma}$ is given by Eq. (1) for each of spin components $\sigma = \uparrow, \downarrow$, and $\hat{n}_{i\sigma} = \hat{c}_{i\sigma}^\dagger \hat{c}_{i\sigma}$. To investigate the superconducting properties we write the Hamiltonian in the single particle eigenbasis of $\hat{H}_{F,\sigma}$, $\hat{c}_{i\sigma} = \sum_n \psi_n(i)\, \hat{c}_{n\sigma}$, and keep only the terms

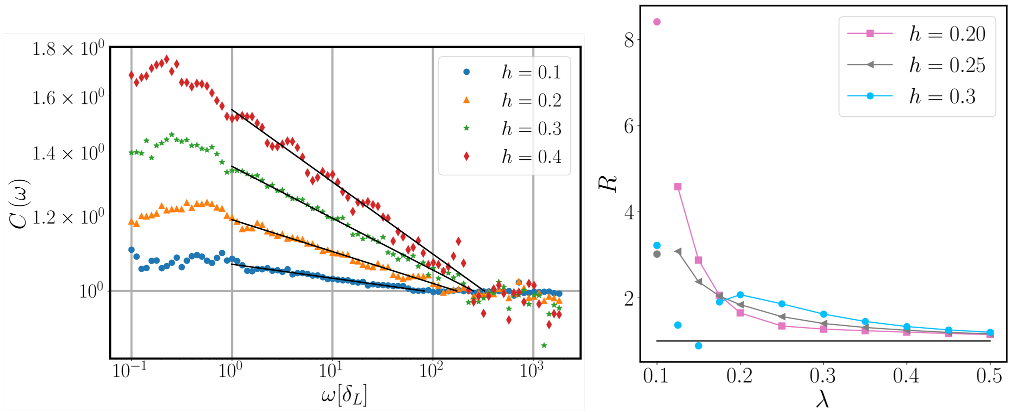

Figure 1: Left: The correlation function (2) of the Fibonacci chain for fixed system size $L = 2000$ and several disorder strengths. The solid black lines are the power-law fits, Eq. (3). The fitted values of γ and E_0 are $\gamma \sim 0.0146,\ 0.0333,\ 0.0542,\ 0.0754$ and $E_0 \sim 82.1,\ 173.3,\ 254.6,\ 325.9\ [\delta_L]$ for $h = 0.1,\ 0.2,\ 0.3,\ 0.4$. Right: The enhancement ratio $R = T_c^N/T_c^A$ vs coupling λ at $L = 4000$ for different disorder strengths h: 0.2 (squares), 0.25 (triangles) and 0.3 (circles). T_c^N is the critical temperature computed numerically, T_c^A is the critical temperature predicted by Eq. (5). The black line corresponds to $R = 1$ and is shown for convenience.

most relevant for the superconductivity

$$\hat{H} = \sum_{n\sigma} \epsilon_n \hat{c}^\dagger_{n\sigma}\hat{c}_{n\sigma} + U \sum_{nm} M_{nm}\hat{c}^\dagger_{n\uparrow}\hat{c}^\dagger_{n\downarrow}\hat{c}_{m\uparrow}\hat{c}_{m\downarrow}$$
$$M_{nm} = \sum_i |\psi_n(i)|^2 |\psi_m(i)|^2,$$

where ϵ_n is the single-particle energy of eigenstate n obtained from Eq. (1). The subscripts n, m label eigenvalues and eigenstate, and the index i is the lattice index. The standard mean-field/BCS approach leads to the gap equation

$$\Delta_n = \frac{|U|}{2} \sum_m \frac{M_{nm}\Delta_m}{\varepsilon_m} \tanh\left(\frac{\epsilon_m}{2T}\right). \qquad (4)$$

where $\varepsilon_m = \sqrt{\epsilon_m^2 + \Delta_m^2}$ is the excitation energy of the superconductor. The superconducting transition is signaled by appearance of a nonzero Δ_n with decreasing temperature T.

The absence of translation invariance in Fibonacci potential, Eq. (1), makes solving the gap equation difficult. Typically one assumes uncorrelated density of states and eigenstates, M_{nm} and Δ_n, self-averaging of the density of states and the gap functions Δ_n. Then the gap equation becomes solvable in the continuous limit after averaging over the disorder realisations:

$$\Delta(\epsilon) = \frac{\lambda}{2} \int_{-\epsilon_D}^{\epsilon_D} \frac{d\epsilon'}{\varepsilon(\epsilon')} C(\epsilon - \epsilon') \tanh\left(\frac{\varepsilon(\epsilon')}{2T}\right) \Delta(\epsilon'). \qquad (5)$$

We compute the critical temperature numerically without a priory assumptions and solve the gap equation (4) in the limit of vanishing gaps $\Delta_n \to 0$,

$$\Delta_n = \frac{\lambda}{2\nu_0} \sum_m^{|\epsilon_m| < \epsilon_D} \frac{M_{nm}}{\epsilon_m} \tanh\left(\frac{\epsilon_m}{2T_c}\right) \Delta_m. \qquad (6)$$

to find the critical temperature T_c numerically for every realization of the Fibonacci potential, and then analyze the statistics of the ensemble of critical temperatures: their distribution function, mean value and variance, as shown in Fig. 1. We observe a clear enhancement of superconducting temperature in the direct numerical solution over the solvable case (5).

[1] Meng Sun, Tilen Čadež, Igor Yurkevich, Alexei Andreanov, Phys. Rev. B 109, 134504 (2024).

2.5 Nanomechanical cat states generated by a dc voltage-driven Cooper pair box qubit

D. Radić, S.-J Choi, H. C. Park, J. Suh, R. I. Shekhter, L. Y. Gorelik

At the nanoscale, electromechanical transduction enters a quantum regime where electron transport becomes strongly coupled to mechanical motion. Nano-electromechanical (NEM) devices harness this interaction to enable functionalities such as tunneling-based actuation, rectification, and single-electron shuttling. The addition of superconductivity introduces qualitatively new behavior: the mechanical motion of a superconducting island can transfer Cooper pairs between electrodes, giving rise to Josephson coupling. This raises fundamental questions about how superconducting qubit dynamics influence—and are influenced by—nanomechanical motion, positioning such systems at the frontier of hybrid quantum technologies.

Recent advances have shown that superconducting qubits can coherently control phonons, enabling phonon-mediated entanglement and quantum state transfer. Mechanical resonators are particularly suited for encoding quantum information in robust Schrödinger cat states—superpositions of multiphonon coherent states with built-in error resilience. This work presents a theoretical proposal for generating such cat states using a Cooper pair box (CPB) qubit coupled to a mechanical oscillator under a dc voltage bias. The system exploits tunable Josephson phase dynamics to entangle the qubit with coherent mechanical states, producing cat-like superpositions. Characterization via Wigner functions and entanglement entropy, along with feasible detection strategies, suggests that NEM–qubit hybrids could serve as powerful platforms for quantum memory and communication.

We study a nanoelectromechanical system where a Cooper pair box (CPB) qubit oscillates between two bulk superconductors. A dc bias voltage drives Josephson phase dynamics,

$$\Phi(t) = \Omega_V t, \qquad \Omega_V = \frac{2|e|V}{\hbar},$$

leading to entanglement between qubit states and coherent states of the mechanical oscillator.

The Hamiltonian reads

$$\hat{H}(t) = \hat{H}_0(t) + \hat{H}_1(t), \tag{1}$$

$$\hat{H}_0(t) = E_J \cos\Phi(t)\,\hat{\sigma}_1 + \frac{\hbar\omega}{2}\left(\frac{\hat{p}^2}{\hbar} + \frac{\hat{x}^2}{\hbar}\right), \tag{2}$$

$$\hat{H}_1(t) = \varepsilon E_J \hat{x}\,\sin\Phi(t)\,\hat{\sigma}_2, \tag{3}$$

where E_J is the Josephson energy, $\hat{\sigma}_i$ are Pauli matrices for the CPB, and $\varepsilon \ll 1$ the electromechanical coupling.

At resonance $\omega = \Omega_V$, the qubit becomes entangled with mechanical coherent states

$$|\Psi(t)\rangle = \sum_{\kappa=\pm} c_\kappa\, |e_\kappa^{(2)}(t)\rangle \otimes |\alpha_\kappa(t)\rangle,$$

with amplitudes $\alpha_\kappa(t) = \kappa\nu t e^{i\omega t}$ and $\nu = \varepsilon E_J/\hbar$. A voltage on–off–on protocol further generates cat states,

$$|\Psi(t)\rangle = \sum_{\kappa=\pm} c_\kappa\Big(\rho\,|\alpha_\kappa(t-T)\rangle + i\tau\,|\alpha_{-\kappa}(t-T)\rangle\Big),$$

with $\rho^2 + \tau^2 = 1$.

The entanglement is quantified by the reduced qubit state

$$\hat{\varrho}_q(t) = \tfrac{1}{2}\left(\hat{I} - \lambda(t)\hat{\sigma}_1\right), \qquad \lambda(t) = e^{-2\nu^2 t^2},$$

yielding entanglement entropy $S_{\text{en}}(t) \to \log 2$ at long times. The mechanical Wigner function exhibits negativity, confirming cat-state formation.

The period-averaged current,

$$\langle I^{(N)}\rangle_T = \frac{e\omega}{2\pi}\Big[\nabla_N(\nu NT)^2 - \tfrac{E_J}{\hbar\omega}\lambda(\nu NT; t_s)\Big],$$

acts as an experimental signature.

Feasibility estimates with GHz mechanical oscillators, Josephson energies 0.1−1 K, and decoherence times $\sim 1\,\mu$s show that nanoamp-scale signals are measurable with present technology. Thus, the proposed mechanism offers

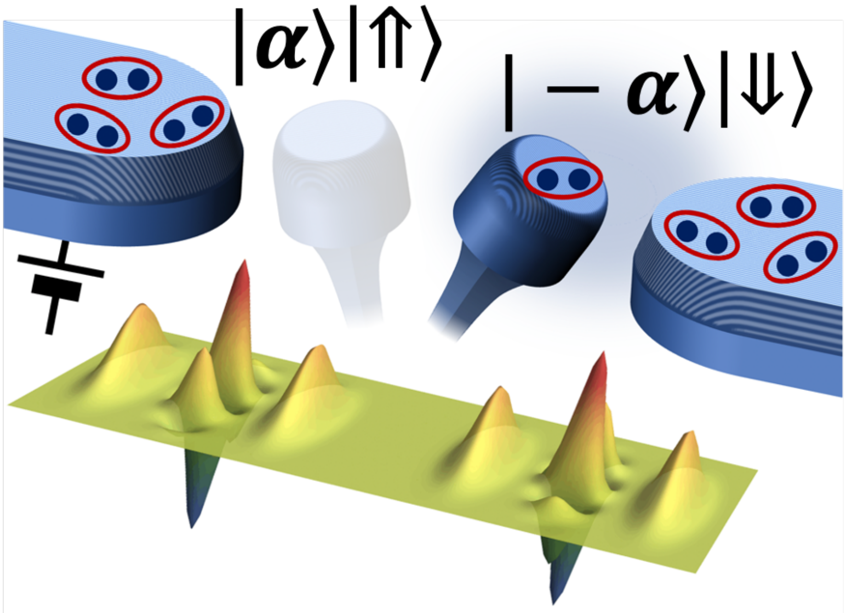

Figure 1: Schematic of the nano-electromechanical system: a Cooper pair box (CPB) qubit oscillates between two bulk superconductors under a dc bias voltage, enabling position-dependent Cooper pair tunneling.

a path to encode superconducting qubit information into robust multiphonon mechanical cat states, with potential applications in quantum communication.

This work investigates a nano-electromechanical system in which a Cooper pair box (CPB) qubit oscillates between two superconductors. By applying a dc bias voltage, the system can generate nanomechanical Schrödinger cat states — superpositions of coherent mechanical vibrations entangled with qubit states. Theoretical analysis (rotating-wave approximation and numerical simulations) shows that resonance between the Josephson frequency and mechanical oscillations leads to macroscopic entanglement. The resulting cat states are confirmed through the Wigner function and quantified by the entropy of entanglement. Importantly, the study proposes an experimental detection scheme: signatures of these states can be observed in the average electric current through the junction. Feasibility estimates, based on realistic CPB parameters and GHz-frequency resonators, indicate that the predicted effects should be observable with existing technology. These results highlight a pathway for encoding quantum information from superconducting qubits into robust multi-phonon mechanical states, offering potential applications in quantum communication.

[1] Danko Radić, Sang-Jun Choi, Hee Chul Park, Junho Suh, Robert I. Shekhter, and Leonid Y. Gorelik, npj Quantum Information **8**, 74 (2022).

2.6 A strain-engineered graphene qubit in a nanobubble

H. C. Park, JY. Han, N. Myoung

Graphene is an attractive candidate for qubits due to its long relaxation and coherence times. Since a qubit requires two discrete quantum states, the formation of graphene quantum dots (QDs) is essential for constructing graphene-based qubits. Although various approaches have been pursued — including etched nanoconstrictions, graphene nanoribbons, and bilayer graphene — these inevitably introduce disorder compared to pristine graphene, hindering precise control.

Strain engineering has emerged as a promising solution. Elastic deformation generates pseudo-magnetic fields (PMFs) in graphene, as confirmed experimentally by the observation of strain-induced Landau levels. Non-uniform PMFs can confine Dirac fermions, and theoretical studies have shown that graphene nanobubbles (NBs) can host localized states. This points to a new class of graphene QDs defined not by lithographic patterning, but by strain.

Another advantage of graphene lies in its mechanical properties: its extremely high elastic modulus (~ 1 TPa), large failure strength (> 100 GPa), and wide elastic strain limit (up to 20%). These features make graphene an ideal candidate for nanoelectromechanical devices, where strain can be used not only for band gap engineering and valleytronics, but also for generating localized quantum states.

We consider an armchair graphene nanoribbon with a Gaussian-shaped nanobubble,

$$z(\mathbf{r}) = h_0 \exp\left(-\frac{r^2}{2\sigma^2}\right),$$

where h_0 is the height and σ the lateral size of the NB. Strain modifies nearest-neighbor hopping amplitudes in the tight-binding Hamiltonian,

$$t_{ij} = t_0 \exp\left[-\beta\left(\frac{d_{ij}}{a_0} - 1\right)\right],$$

with t_0 the unstrained hopping, a_0 the lattice constant, and $\beta \approx 3.37$.

The deformation acts as an effective gauge field $\mathbf{A}_{\mathrm{ps}}$ that couples to Dirac fermions, giving rise to a pseudo-magnetic field

$$\mathbf{B}_{\mathrm{ps}} = \nabla \times \mathbf{A}_{\mathrm{ps}},$$

which has opposite sign in the two valleys K and K'. In the NB geometry, the strongly non-uniform PMF confines Dirac fermions and creates discrete localized states.

When two such localized states appear, they form a *double quantum dot* (DQD). This DQD can be modeled as a *two-level system* (TLS) described by

$$\hat{H}_{\mathrm{TLS}} = \frac{\Delta}{2}\,\hat{\sigma}_z + t\,\hat{\sigma}_x,$$

where Δ is the energy detuning between the two localized states and t is the tunnel coupling strength. The eigenenergies

$$E_{\pm} = \pm\tfrac{1}{2}\sqrt{\Delta^2 + 4t^2}$$

show an avoided crossing as Δ passes through zero, the hallmark of qubit formation in this system.

Electrostatic gates allow external control of Δ, while strain modulates both Δ and t by reshaping the PMF profile. Thus, the NB-based TLS is controllable through both electrical and mechanical means, making it a highly tunable graphene qubit platform.

In conclusion, strain-engineered nanobubbles in pristine graphene offer a robust, disorder-free route to qubit realization. Such devices combine mechanical tunability, ultrafast operation, and long coherence times, pointing toward a promising direction for graphene-based quantum technologies.

Beyond the immediate demonstration of avoided crossings, Landau–Zener splitting control, and picosecond-scale Rabi oscillations, this work establishes a general framework for using mechanical strain to define quantum degrees of freedom in otherwise gapless two-dimensional materials. Unlike etched

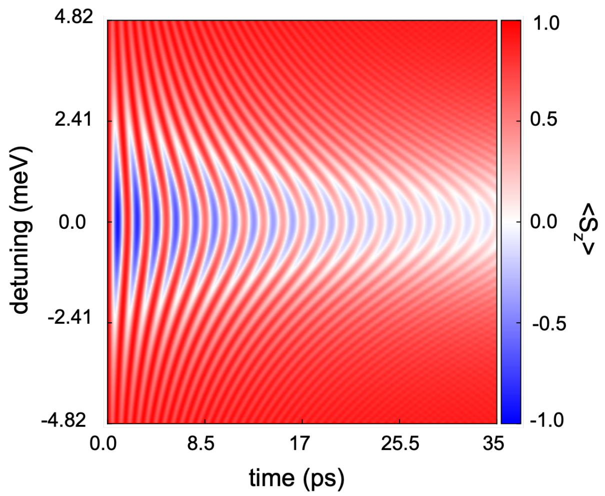

Figure 2: Rabi oscillation map showing S_z expectation values defined in the concept of a Bloch sphere. $\langle S_z \rangle = 1$ indicates that the TLS resides in the $|\psi_+\rangle$ state, i.e., an excited state. The zero detuning implies that the two QDs in the NB are set to be identical for the TLS formation at the avoided crossing point.

nanostructures or bilayer devices, nanobubble-induced quantum dots preserve the intrinsic quality of monolayer graphene, minimizing disorder and decoherence. The dual control via both electrostatic gates and mechanical strain provides exceptional flexibility for quantum state manipulation, bringing together electronic, mechanical, and valley degrees of freedom.

From a technological perspective, this approach suggests a pathway toward scalable graphene qubit architectures integrated with nanoelectromechanical systems (NEMS). Arrays of nanobubbles could, in principle, be engineered to realize networks of coupled TLSs, enabling multi-qubit interactions. Furthermore, the strain-tunable energy spectrum makes the system suitable for implementing non-adiabatic control protocols, such as Landau–Zener–Stückelberg interference, for fast and high-fidelity qubit operations.

More broadly, the results highlight the potential of strain engineering as a universal strategy for quantum material design. By exploiting localized states generated by PMFs, one can envision hybrid architectures where graphene qubits are coupled to optical cavities, superconducting resonators, or phononic modes, thereby bridging condensed-matter physics with quantum communication and quantum sensing. This line of research thus not only demonstrates a specific qubit realization, but also sets the stage for the development of next-generation strain-defined quantum devices.

[1] Hee Chul Park, JungYun Han, and Nojoon Myoung, Quantum Sci. Technol. 8, 025012 (2023).

2.7 The proposal for the photoinduced anomalous supercurrent Hall effect

A. V. Parafilo, M. V. Boev, I. G. Savenko

The optical response of superconductors is a key tool to probe their quantum properties, yet the interaction between electromagnetic fields and superconductors remains difficult because superconducting samples expel external fields. Understanding this coupling is essential for both fundamental studies and potential light-controlled transport of Cooper pairs. Proposed nonlinear and higher-order optical effects include electric-field-induced enhancement of superconductivity, second-harmonic generation under supercurrent injection, and light-mediated superconductivity. Another possible route is the photoinduced anomalous Hall effect, where a dc supercurrent develops a Hall-like transverse component.

In non-superconducting materials, the anomalous Hall effect appears as a transverse current without magnetic fields, driven by spin–orbit coupling or valley polarization, and photoinduced variants have been demonstrated in several systems. However, in clean single-band Bardeen–Cooper–Schrieffer superconductors, particle–hole and inversion symmetries forbid momentum-conserving optical transitions. Such transitions become possible only when inversion symmetry is broken or when impurity scattering or multiband effects intervene.

Mattis and Bardeen showed that optical absorption across the superconducting gap vanishes in the clean limit because electron- and hole-like states are orthogonal, while impurity scattering restores finite absorption, as confirmed experimentally. Even in clean superconductors, inversion breaking or spin–orbit coupling can allow optical transitions, but Galilean invariance in parabolic bands suppresses them. Hence, realizing a photoinduced Hall-like response requires a mechanism breaking inversion, time-reversal, and Galilean symmetries, for example through weak impurity scattering.

We showed that even in a single-band BCS superconductor, the breaking of both inversion and time-reversal symmetries by means of a built-in supercurrent, and the breaking of Galilean invariance by (weak) electron-impurity scattering, results in photoinduced transport of Cooper-pair condensate in the direction transverse to the built-in supercurrent [1]. Hereby we defined the photoinduced anomalous suppercurrent Hall effect. At the temperatures $T \ll \Delta$ with Δ the SC order parameter, the equilibrium density of quasiparticiples above the gap is negligibly small in the absence of external radiation. Therefore, we expect that the photoinduced Hall response should be determined by the inelastic quasiparticle relaxation time τ_R associated with the recombination processes of quasiparticles across the gap. It is important to note, that large τ_R at sufficiently low temperatures provides large values of the supercurrent, opening a way for the experimental verification of its existence.

The idea behind the supercurrent Hall effect can be roughly explained using phenomenological arguments. Let us consider a 2D layer with a built-in stationary supercurrent generated either by, e.g., a transport current or an external applied magnetic field. The supercurrent is the consequence of nonzero supermomentum $\mathbf{p}_s$ of the Cooper pairs, associated with the phase difference of the condensate at the edges of the sample.

Furthermore, if an isotropic 2D superconductor in supercurrent-carrying regime is normally illuminated by an external EM radiation characterized by the in-plain vector potential $\mathcal{A}(t) = \mathcal{A}\exp(-i\omega t) + \mathcal{A}^* \exp(i\omega t)$, the photoinduced stationary current of quasiparticles excited across the SC gap in the most general form reads as

$$\mathbf{j} = a_\omega|\mathcal{A}|^2\mathbf{p}_s + b_\omega[\mathcal{A}(\mathcal{A}^* \cdot \mathbf{p}_s) + (\mathcal{A} \cdot \mathbf{p}_s)\mathcal{A}^*] + ic_\omega[\mathbf{p}_s \times [\mathcal{A} \times \mathcal{A}^*]]. \quad (1)$$

The first term in Eq. (1) gives the longitudinal (aligned along the supercurrent flow) photoexcited current density; the second term contains both the longitudinal and transverse quasiparticle current density responses; the third term gives only the transverse response. Anisotropic contributions characterized by the terms proportional to coefficients b_ω and c_ω are induced by linearly and circularly polarized radiation, respectively. Note, that Eq. (1) is valid only for relatively small values of the supercurrent density, $|\mathbf{p}_s|v_F \ll \Delta$, where v_F is electron Fermi velocity.

We focus on the transverse component of the current (1), $j_y = b_\omega(\mathcal{A}_x\mathcal{A}_y^* + \mathcal{A}_x^*\mathcal{A}_y)p_s + ic_\omega(\mathcal{A}_x\mathcal{A}_y^* - \mathcal{A}_x^*\mathcal{A}_y)p_s$ by choosing the direction of condensate flow along the x-axis, $\mathbf{p}_s = (p_s, 0)$. Using the terminology of the two-fluid model, we call j_y the photoexcited current of quasiparticles contributing to the normal component of electron fluid. It provides an accumulation of carriers of charge at the transverse boundaries of the sample. In the case of a non-SC material, such an accumulation results in the emergence of the Hall electric field. In the case of a SC material, instead, the electric field cannot penetrate the SC sample. Therefore, the transverse quasiparticle current j_y should be accompanied by an induced *transverse* condensate flow j_s in such a way, that the Hall electric field is compensated, thus $j_s + j_y = 0$, and the net transverse electric current vanishes.

Furthermore, even though the net current vanishes, the emergence of j_s produces the condensate phase difference on the transverse boundaries of the sample, $\Delta\phi_H \propto -j_y w$, where w is the width of the 2D SC sample across $\mathbf{p}_s$ in y direction. The Hall-like condensate phase difference $\Delta\phi_H$ directly relates to the coefficients b_ω and c_ω, which determine the quasiparticle optical response across the SC gap. In what follows, let us build a microscopic theory to find c_ω, thus considering circularly polarized EM field.

In the absence of relaxation processes, the Hamiltonian of a 2D superconductor with an isotropic s-type BCS pairing exposed to an external EM field reads (in $\hbar = k_B = c = 1$ units)

$$\hat{H} = \begin{pmatrix} \xi(\mathbf{p} - \mathbf{p}_s - e\mathcal{A}(t)) & \Delta \\ \Delta & -\xi(\mathbf{p} + \mathbf{p}_s + e\mathcal{A}(t)) \end{pmatrix}. \quad (2)$$

Here, $\xi(\mathbf{p}) \equiv \xi_p = \mathbf{p}^2/2m - E_F$ is the electron kinetic energy measured from the Fermi energy E_F, and Δ we assume real-valued. The current density operator and the current density obey the standard relations,

$$\hat{\mathbf{j}} = -\frac{\delta \hat{H}}{\delta \mathcal{A}}, \qquad \mathbf{j}(t) = -i\,\mathrm{Sp}\left\{\hat{\mathbf{j}}\,\hat{\mathcal{G}}^<(t,t)\right\}, \quad (3)$$

where $\hat{\mathcal{G}}^<(t,t)$ is a lesser component of the Green's function defined by the matrix equation $(i\partial_t - \hat{H})\hat{\mathcal{G}}(t-t') = \delta(t-t')$ in the Nambu and Keldysh representation.

In the absence of impurities, a single-band superconductor with parabolic electron dispersion possesses the Galilean invariance with or without a built-in supercurrent. Consequently, optical absorption vanishes in both cases. Meanwhile, the second-order stationary response is a consequence of photoabsorption across the gap. Thus, it vanishes in clean case both in the absence and presence of the supercurrent. The optical absorption and the photoinduced electric current (1) acquire finite values when the Galilean invariance is violated. We considered the case when it happens due to the presence of electron-impurity scattering in the sample.

To find the photocurrent in the presence of impurities, we accounted for electron scattering and relaxation processes associated with the transition of photoexcited quasiparticles to the SC condensate in the Green's function in Eq. (3). All the relaxation processes are characterized by the parameter

$$\frac{1}{\tau_p} = \frac{1}{\tau_i}\frac{|\xi_p|}{\epsilon_p} + \frac{1}{\tau_R}, \quad (4)$$

where the first term describes the quasiparticle relaxation due to the scattering off impurities, while the second term accounts for the recombination back to the condensate, characterized by the parameter τ_R. The dominant inelastic process is the recombination across the SC gap, characterized by τ_R since $\tau_p = \tau_i\tau_R\epsilon_p/(\tau_R|\xi_p| + \tau_i\epsilon_p) \approx \tau_R$ at $|\xi_p| \to 0$.

[1] A. V. Parafilo, V. M. Kovalev, and I. G. Savenko, Phys. Rev. B Letters 108, L180509 (2023)

2.8 A proposal for a superconducting photodiode

A. V. Parafilo, M. V. Boev, I. G. Savenko

A semiconducting diode has a p–n junction that conducts current mainly in one direction, enabling rectification in electronic circuits. A superconducting (SC) diode, in contrast, works without a p–n junction, allowing asymmetric flow of Cooper-pair supercurrent and thus diode-like behavior. Recent advances have demonstrated such rectification in superconductors, suggesting new circuit designs, while the photoresponse of SC materials remains challenging since uniform electromagnetic fields couple weakly to them, making efficient light–matter interaction an important goal.

We considered the nonlinear contribution in the external EM field amplitude. To demonstrate the sensitivity of the proposed photodiode to the frequency and polarization of an external EM field, we studied the properties of photoinduced anomalous transverse transport of Cooper pairs [1]. We considered an isotropic 2D layer below the SC critical temperature T_c but at a finite temperature T and with a given (source) stationary current of Cooper pairs $\mathbf{j}_s$ in the x-direction. Furthermore, the sample was illuminated by an external EM field, described by the vector-potential $\mathcal{A}(t) = \mathcal{A}\exp(-i\omega t) + \mathcal{A}^*\exp(i\omega t)$ at a normal incidence. Since there is a finite amount of thermally excited quasiparticles above the SC gap Δ at $T \neq 0$, we can restrict ourselves to considering $\omega \ll \Delta/\hbar$. The EM field is circularly polarized, $\mathcal{A} = \mathcal{A}_0(1, i\sigma)$, where $\sigma = \pm 1$ stands for the left/right circular polarization. As a result of the light absorption by the sample, a photoinduced electric current of electrons above the SC gap emerges, the stationary part of which reads

$$\mathbf{j} = ic_\omega[\mathbf{p}_s \times [\mathcal{A} \times \mathcal{A}^*]], \tag{1}$$

where $\mathbf{p}_s = (p_s, 0)$ is the Cooper pairs' momentum. Phenomenological expression (1) describes the stationary photoinduced electric current in the system due to the emergence of a correction to the electron distribution function, $\delta f(\mathbf{v}, \mathbf{E}, \mathbf{p}_s) \propto (\mathbf{v}\cdot\mathbf{E})(\mathbf{v}\cdot\mathbf{E}^*)(\mathbf{v}\cdot\mathbf{p}_s)$, which refers to the phenomenon called *the anisotropic alignment of photoelectrons*. It provides the accumulation of positive and negative charges at the transverse boundaries of the sample.

Since the electric field nearly cannot penetrate the SC sample, the current of photoinduced quasiparticles (1) should be accompanied by an induced condensate flow so that the electric field is compensated, following the general properties of superconductors. As a result, there emerges a flow of a frequency- and polarization-controlled unidirectional electric current of Cooper pairs $\mathbf{j}_\mathrm{p}$. Indeed, the photoinduced quasiparticle current (1) as a response to the circularly-polarized EM field, must vanish both at zero frequencies, $\omega \to 0$, and large frequencies, $\omega \to \infty$. It also changes its sign if the built-in supercurrent changes its direction to the opposite one, $\mathbf{j}_s \to -\mathbf{j}_s$.

The Hamiltonian of a single-band isotropic 2D s-wave superconductor exposed to an external EM field reads ($\hbar = k_B = c = 1$)

$$\hat{H} = \begin{pmatrix} \xi(\mathbf{p} - \mathbf{p}_s - e\mathcal{A}(t)) & \Delta \\ \Delta & -\xi(-\mathbf{p} - \mathbf{p}_s - e\mathcal{A}(t)) \end{pmatrix}, \tag{2}$$

where $\xi(\mathbf{p}) \equiv \xi_\mathbf{p} = \mathbf{p}^2/2m - E_F$ is the electron kinetic energy, E_F is the Fermi energy, and Δ is a SC gap, which we assume to be real-valued. The electric current density is determined as the trace of the current operator with a "lesser" component of the Green's function,

$$\mathbf{j}(t) = -i\,\mathrm{Tr}\left\{\hat{\mathbf{j}}\,\hat{\mathcal{G}}^<(t,t)\right\}. \tag{3}$$

In Eq. (3), the operator of the current represents the variation of the Hamiltonian (2) over the vector-potential,

$$\hat{\mathbf{j}} = -\frac{\delta\hat{H}}{\delta\mathcal{A}} = e\mathbf{v} - \frac{e\mathbf{p}_s}{m}\hat{\tau}_z - \frac{e^2\mathcal{A}}{m}\hat{\tau}_z, \tag{4}$$

and $\hat{\mathcal{G}}^<(t,t')$ is the lesser component of the Keldysh Green's function $\hat{\mathcal{G}}(t,t')$ determined by the equation $(i\partial_t - \hat{H})\hat{\mathcal{G}}(t,t') = \delta(t-t')$.

Expanding $\hat{\mathcal{G}}(t,t')$ up to the first order with respect to $\mathbf{p}_s$ and up to the second order with respect to $\mathcal{A}(t)$ yields the total current density.

The resulting components of the current density read

$$\mathbf{j}^{(a,b)} = ie^3\sum_{\mathbf{p}}\int dt_1\int dt_2 \mathrm{Tr}\left\{\hat{\gamma}^{(a,b)}\hat{g}(t,t_1)\times\hat{\gamma}_{\pm}^{(a,b)}\hat{g}(t_1,t_2)\hat{\gamma}_{\mp}^{(a,b)}\hat{g}(t_2,t)\right\}^<, \quad (5)$$

$$\mathbf{j}^{(c)} = \frac{ie^3}{m}\sum_{\mathbf{p}}\int dt_1 \, \mathrm{Tr}\left\{\hat{\gamma}^{(c)}\hat{g}(t,t_1)\hat{\gamma}_{-}^{(c)}\hat{g}(t_1,t)\right\}^<, \quad (6)$$

where $\hat{g}(t,t')$ is a bare Keldysh Green's function, which represents a solution of the equation $(i\partial_t - \hat{H})\hat{g}(t,t') = \delta(t-t')$ with the Hamiltonian (2), in which $\mathbf{p}_s = 0$ and $\mathcal{A}_0 = 0$; $\gamma^{(a,b,c)}_{,+,-}$ are generalised vertices: $\hat{\gamma}^{(a)}=\mathbf{v}$, $\hat{\gamma}^{(b,c)}=\mathcal{A}\hat{\tau}_z$, $\hat{\gamma}_{+}^{(a,b)}=(\mathbf{v}\cdot\mathcal{A})$, $\hat{\gamma}_{-}^{(a,c)}=(\mathbf{v}_s\cdot\mathcal{A})\hat{\tau}_z$, $\hat{\gamma}_{-}^{(b)}=(\mathbf{v}\cdot\mathbf{v}_s)$, with $\mathbf{v}_s=\mathbf{p}_s/m$. Furthermore, in Eqs. (5) and (6) let us shift to the energy-momentum representation and consider the first stationary photo-induced correction to the current density. Direct calculation of the current density using the bare Green's function $\hat{g}_\epsilon = (\epsilon - \Delta\hat{\tau}_x - \xi_{\mathbf{p}}\hat{\tau}_z)^{-1}$ gives a vanishing contribution, as expected: The selection rules forbid optical absorption in the superconductor due to preserving the Galilean invariance even in the case of broken spatial symmetry ($\mathbf{p}_s \neq 0$).

The Galilean invariance can be broken by an account of either i) non-parabolicity of the electronic dispersion, or ii) multi-bands, or iii) impurities. We will use the latter mechanism (the scattering on non-magnetic impurities). Solving the Dyson equation and averaging over the disorder potential, we find the retarded, advanced, and lesser Green's function of electrons in 2D superconductor:

$$\hat{g}_\epsilon^R = \frac{\epsilon\eta_\epsilon + \xi_{\mathbf{p}}\hat{\tau}_z + \Delta\eta_\epsilon\hat{\tau}_x}{\left(\epsilon - \epsilon_{\mathbf{p}} + \frac{i}{2\tau_{\mathbf{p}}}\right)\left(\epsilon + \epsilon_{\mathbf{p}} + \frac{i}{2\tau_{\mathbf{p}}}\right)}, \quad (7)$$

$$\hat{g}_\epsilon^A = \left(\hat{g}_\epsilon^R\right)^*, \qquad \hat{g}_\epsilon^< = -f_\epsilon\left(\hat{g}_\epsilon^R - \hat{g}_\epsilon^A\right).$$

Here, $\epsilon_{\mathbf{p}} = \sqrt{\xi_{\mathbf{p}}^2 + \Delta^2}$ is the quasiparticles dispersion, $\tau_{\mathbf{p}}$ is their effective lifetime, $f_\epsilon = [\exp(\epsilon/T)+1]^{-1}$ is the Fermi-Dirac distribution function,

$$\eta_\epsilon = 1 + \frac{i}{2\tau_i}\frac{\mathrm{sign}[\epsilon]}{\sqrt{\epsilon^2-\Delta^2}} \quad (8)$$

is a renormalization factor, which accounts for the disorder with $\tau_i = (2\pi\nu_0 n u_0^2)^{-1}$ the characteristic time of electron scattering on impurities with ν_0 is the density of states of electron gas in non-SC state, n is the density of impurities, u_0 is the impurity electrostatic potential.

However, the elastic scattering (characterized by τ_i) is not the only mechanism, and, in general, various relaxation processes may play role in a SC sample exposed to an EM field. Which particular relaxation time makes a dominant contribution depends on the frequency of the EM field, the properties of the SC sample, and how the frequency is related to the SC gap. At small frequencies $\omega \ll \Delta$ and the temperatures in the vicinity of the SC critical temperature T_c, the optical conductivity depends on the inelastic relaxation time τ_E, which is, in turn, determined by the energy relaxation of quasiparticles in 2D films. Altogether, the relaxation processes are described by the effective inverse lifetime,

$$\frac{1}{\tau_{\mathbf{p}}} = \frac{1}{\tau_E} + \frac{1}{\tau_i}\frac{|\xi_{\mathbf{p}}|}{\epsilon_{\mathbf{p}}}. \quad (9)$$

Substituting $\tau_{\mathbf{p}}$ in equations above and performing calculations, we found:

$$j_y^{(a)} + j_y^{(b)} = \frac{4j_0\omega\tau_E}{\left[1+(\omega\tau_E)^2\right]^2}\frac{\tau_E}{\tau_i}\left(\frac{\Delta}{2T}\right)^2\mathcal{I}_1\left(\frac{\Delta}{2T}\right), \quad (10)$$

$$j_y^{(c)} = \frac{j_0}{2}\frac{\omega\tau_E}{1+(\omega\tau_E)^2}\frac{1}{(2T\tau_i)^2}\left(\frac{\Delta}{2T}\right)^2\mathcal{I}_2\left(\frac{\Delta}{2T}\right), \quad (11)$$

where $j_0 = \sigma(e^3 p_s\mathcal{A}_0^2/m\pi)$, and the dimensionless integrals read

$$\mathcal{I}_1(y) = \int_y^\infty \frac{dx}{x^2\cosh^2(x)}, \quad (12)$$

$$\mathcal{I}_2(y) = \int_y^\infty \frac{dx}{x^3\cosh^2(x)}\frac{1}{\sqrt{x^2-y^2}}. \quad (13)$$

Eqs. (10) and (11) also account for the temperature dependence of the SC gap, $\Delta(T) = \Delta_0\tanh\left(1.76\sqrt{T_c/T-1}\right)$ with $\Delta_0\equiv\Delta(T{=}0)$ and $T_c = \Delta_0(\exp[0.577]/\pi)$. The emergent photodiode supercurrent reads as $j_p = -\left(j_y^{(a)} + j_y^{(b)} + j_y^{(c)}\right)$.

Formulas (10) and (11) describe the main contributions to the photodiode current density and constitute the main result of this work.

[1] A. V. Parafilo, M. Sun, K. Sonowal, V. M. Kovalev and I. G. Savenko, 2D Mater. 12, 011001 (2024).

2.9 Quantum Charging Advantage Cannot Be Extensive without Global Operations

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Quantum batteries are devices made from quantum states, which are used to store and release energy on demand. They have attracted a significant amount of attention in recent years, since they offer a significant charging speedup whenever entangling operations are used in the charging process, thus creating an instance of a *quantum advantage.* In [1] it was rigorously shown that the maximal possible speedup is extensive in the number of individual quantum cells making the battery, thus offering at most quadratic scaling in the charging power over the classically achievable linear scaling. To reach such a scaling, a global charging protocol, charging all the cells collectively, must be employed.

More concretely, the quantum charging advantage can be quantified by studying the ratio, Γ, between the charging power obtained via a given charging protocol and the power obtained by means of non-entangling operations. It was already known in the literature that a general bound on Γ reads

$$\Gamma \leq \gamma \left(k^2(m-1)+k\right) , \tag{1}$$

where γ is a model-dependent constant, k is the maximum number of cells that are collectively charged (thus denoting the presence of *global* charging operations), while m (called participation number) is the maximum number of parallel charging operations in which a single cell appears. However, it was already known that the bound above is quite loose and not very informative.

In [1], it has been shown that a general quantum charging provides at most an extensive advantage over classical charging. Furthermore, it has been shown that this scaling is achievable only via global charging operations, *i.e.*, all-to-all interactions – and more generally, the participation number – do not play any role in generating a quantum charging advantage. In concrete, [1] improves the bound of Eq. (1) to the following, more stringent bound

$$\Gamma \leq \gamma k \, , \tag{2}$$

thus making evident that the maximal charging advantage scales *linearly* with the number of quantum cells.

The result above, which provides a rigorous proof of a conjecture that was open in the literature for more than 5 years, has been obtained by first proving the following general result, which applies to a completely generic charging process driven by a charging Hamiltonian $\hat{V}(t)$, even beyond the case of a battery made of several independent cells

$$|P(t)| \leq \Delta E \, ||V(t)|| \ , \tag{3}$$

where $P(t)$ refers to the charging power at the time t, $||V(t)||$ refers to the operator norm of the charging Hamiltonian $\hat{V}(t)$ (and it can always be redefined in a way that it does not play any non-trivial role) and ΔE is the *maximum* energy jump that can be induced, in a single time step, by $\hat{V}(t)$. This latter term represents the crucial ingredient in the study of the charging power. While non-trivial to prove, this result is very intuitive a posteriori. The charging power is the amount of energy stored in the battery in a single time step. Thus, this change in energy must be bounded by the maximum amount of energy that the driving term can transfer to the system during that time. The bound in Eq. (2) can be finally obtained as a simple corollary of the much more general result described in Eq. (3).

In summary, this result has concluded the quest on the limits of charging power of quantum batteries and has added to other results in which quantum methods are known to provide at most quadratic scaling over their classical counterparts.

[1] J. Y. Gyhm, D. Šafránek and D. Rosa, Phys. Rev. Lett. **128**, no.14, 140501 (2022).

2.10 Micromasers as Quantum Batteries

Vahid Shaghaghi, Varinder Singh, Giuliano Benenti, Dario Rosa

The paper [1] studies the possibility of building new efficient architectures of quantum batteries. A quantum battery is a quantum mechanical system suitable to store energy in some of its highly excited states, to be released on demand. In the literature, several models of quantum batteries have been proposed and studied, and their relevant figures of merit have been extensively investigated.

On a more practical level, proposals to concretely build quantum batteries have emerged, including models realized by spin chains and qubit systems charged by electromagnetic fields. However, with some very recent limited exceptions, achievements on actual experimental realizations have been limited. In [1], a well-known and well-studied model – the *micromaser* – has been re-explored and reinterpreted as a quantum battery architecture. In a micromaser, a stream of qubits (two-level atoms in cavity QED) sequentially interact with a cavity mode with a high-quality factor. That is, the radiation decay time is much larger than the characteristic time of the qubit–field interaction, and the overall evolution is, to a good approximation, coherent. [1] shows that a micromaser can be quickly charged to reach an *almost steady state*, whose energy is controlled by the physical parameters defining the model. The possibility of reaching an (almost) steady state is crucial to ensure the stability of the energy stored in the battery, without unwanted temporal fluctuations. Moreover, and crucially, the almost steady states are approximately pure and therefore, in principle, almost all their energy can be reversibly extracted. This is a very surprising feature, since dynamics in micromasers involve a trace over qubit degrees of freedom after each interaction.

These surprising and important results are obtained numerically, even in the so-called *ultra-strong coupling limit*, in which the atom-field dynamics is described by the following Rabi Hamiltonian in the interaction picture:

$$\hat{H}_I = g\left(\hat{a}\hat{\sigma}_+ + e^{2i\omega t}\hat{a}^\dagger\hat{\sigma}_+ + \text{h.c.}\right), \quad (1)$$

where g denotes the interaction strength, $\hat{a}\dagger$ and $\hat{a}$ are the creation/annihilation operators for the field, $\hat{\sigma}_+$ is the raising operator for the qubit, and ω is the (resonant) frequency of the qubits and of the field.

The dynamics of the field can be mathematically described in terms of the following, non-unitary, discrete map

$$\hat{\rho}_B(k+1) = \text{Tr}_q\left(\hat{U}_I(g,\omega)\hat{\rho}_B(k)\hat{U}_I^\dagger(g,\omega)\right), \quad (2)$$

where the unitary operator $\hat{U}_I(g,\omega)$ is the operator governing the dynamics of the field and of the $(k+1)$ qubit, as described by the interaction Hamiltonian Eq. (1), and the operation Tr_q denotes the partial trace over the qubit degrees of fredom, thus leaving with the state of the field after the qubit has left the cavity.

As already anticipated, the dynamics described by the Rabi Hamiltonian Eq. (1) cannot be solved analytically, and it becomes mandatory to investigate it numerically. On the other hand, in the weak-coupling limit $g \ll 1$, the dynamics turns out to be equivalent to the so-called Jaynes-Cummings (JC) Hamiltonian, which can be solved analytically, and for which the presence of special *trapping states* is known.

The results of this numerical investigation are reported in Fig. 1.

In panel (a), it is shown that, even for values of g/ω outside of the weak-coupling limit, the dynamics still can lead to some sort of metastable steady state, with the energy that remains constant for a large number of collisions before leaving the metastable state. Interestingly, the degree of stability of the metastable state is controlled not only by the ratio g/ω, but also by the coupling parameter g itself. Interestingly, these metastable states are characterized by high levels of purity, as clearly visible from the analysis of the pu-

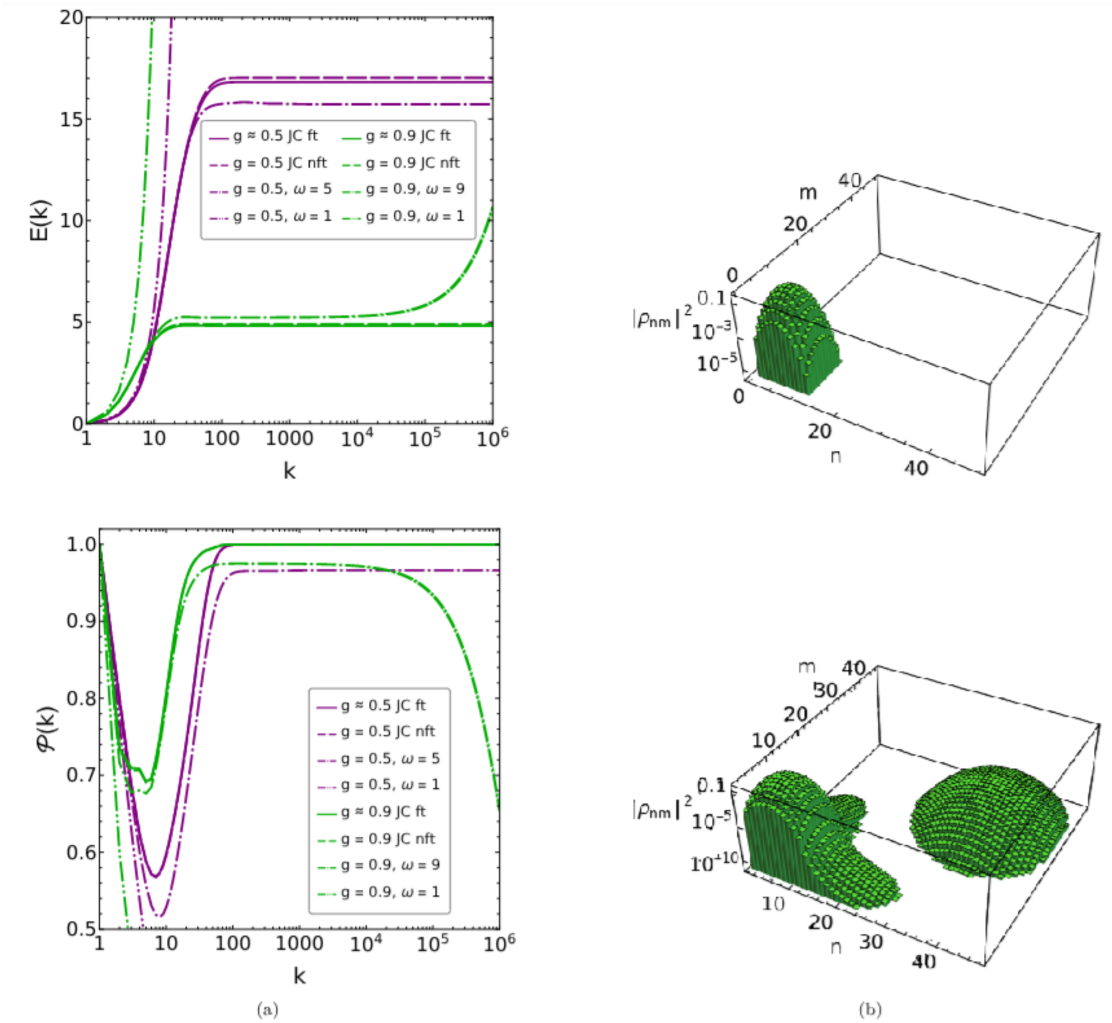

Figure 1: A summary of the charging performance of the micromaser quantum battery.

rity quantifier $\mathcal{P}(k) = \mathrm{Tr}\left(\hat{\rho}^2(k)\right)$. These findings can be better understood by studying the distribution of the absolute values of the density matrix elements, $|\hat{\rho}_{mn}|^2$, in the metastable states, as shown in panel (b): the dynamics, although far from the JC regime, still feel the presence of the trapping states characteristic of the JC Hamiltonian. In this situation, the field state remains confined for a long time to a single trapping chamber, and therefore, it cannot increase its energy anymore, while the interaction with the incoming qubits serves now to build purity. Eventually, the trapping condition is lost, and the evolution is then free to explore subsequent trapping chambers.

All in all, these results support the idea that a micromaser can serve as an excellent framework to build a quantum battery; perhaps with an easier implementation in current experimentally accessible architectures.

[1] V. Shaghaghi, V. Singh, G. Benenti and D. Rosa, Quantum Sci. Technol. **7**, no.4, 04LT01 (2022).

2.11 Bloch theorem dictated wave chaos in microcavity crystals

Chang-Hwan Yi, Hee Chul Park, Moon Jip Park

This work extends wave-chaos physics from single deformed microcavities to periodic microcavity lattices. The authors demonstrate that Bloch momentum acts as a tunable knob that adiabatically deforms internal cavity states, hybridizes degenerate scar modes, and induces a dynamical localization transition. At Brillouin-zone boundaries, maximal momentum coupling reshapes intracavity field patterns and produces parity-selected regular states as well as flat-band segments. Controlled boundary deformations convert symmetry-protected quadratic band touching (QBT) into pairs of Dirac nodes, and further symmetry breaking generates a Berry-curvature dipole that drives skew light transport. Microcavity crystals thus emerge as a versatile platform for in situ control of wave chaos, topology, and photonic transport.

In isolated microcavities, wave chaos is engineered by lithographic boundary deformation, which modifies the mixed regular/chaotic structure of ray dynamics and produces scar modes. The conceptual advance here is that Bloch's theorem introduces an "external knob": the total wavefunction factorizes as

$$\Psi_{\rm tot}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}}\psi_{\rm int}(\mathbf{r}),$$

so tuning lattice momentum $\mathbf{k}$ acts as an effective deformation that breaks or restores internal rotational symmetries. This cavity–momentum locking substitutes for physical boundary changes and is continuously tunable.

The system is a square lattice of dielectric microcavities (TM polarization) with refractive index ratio $n_{\rm in}/n_{\rm out} = 10$ and lattice constant $a = 2.2R$. Each cavity boundary carries a C_4 deformation of strength ε. Mode spectra and fields are obtained via a boundary-element method with periodic boundary conditions.

For small ε, a single cavity supports two degenerate scar modes associated with a period-2 unstable orbit. At $\mathbf{k} = \Gamma$, these appear as degenerate lattice modes. Finite momentum lifts the degeneracy and hybridizes them into bow-tie–like period-4 orbits. An effective two-level Hamiltonian captures the hybridization, and the spinor texture exhibits a 2π Berry phase enforcing a C_4-protected QBT.

At X and Y points, Bloch conditions enforce anti-periodicity. The scar combinations reorganize into even- and odd-parity states. Even-parity modes are confined and yield an almost flat band along X–M, while odd-parity modes shift weight outward, lowering energy. At M, global C_4 symmetry restores the QBT.

Introducing a small boundary deformation drives topological transitions. Even-N deformations split the QBT into two Dirac points, whereas odd-N deformations gap them, producing finite Berry curvature with zero monopole charge but a nonzero Berry-curvature dipole. This dipole acts as an effective field in semiclassical dynamics, generating skew-symmetric beam transport controllable by incident momentum.

Cavity–momentum locking enables in situ phase-space control of wave chaos without refabrication. The scar-state spinor furnishes a minimal symmetry-protected unit that demonstrates dynamical localization transitions. Momentum-selective confinement yields nearly flat bands, promising for enhanced light–matter interaction and nonlinear optics. Berry-curvature dipoles in the Mie regime open a path to nonlinear Hall-type photonic transport.

Future directions include: (i) non-Bravais lattices (e.g., Lieb, Kagome) with intrinsic flat bands; (ii) dynamical tunneling under momentum ramps; (iii) non-Hermitian extensions probing exceptional-point physics; and (iv) active devices exploiting skew scattering for nonreciprocal beam steering. Together, these results establish microcavity crystals as a powerful testbed for studying wave chaos, topology, and functional photonics.

[1] Chang-Hwan Yi, Hee Chul Park, and Moon Jip Park, Light: Science & Applications 12, 106 (2023); arXiv:2203.14861

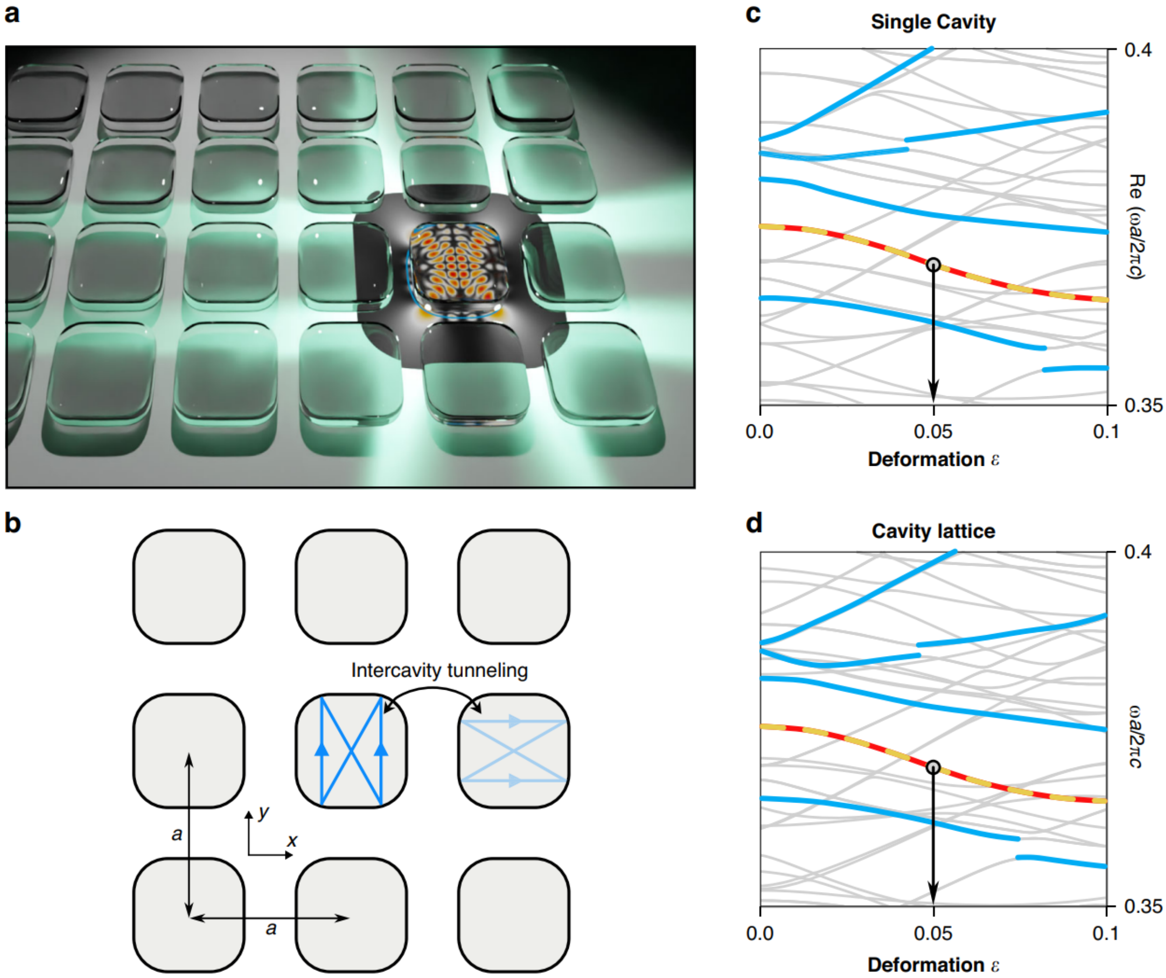

Figure 1: Bloch theorem dictated scar lattice. a Conceptual illustration of a photonic crystal consisting of a deformed dielectric microcavities. b Schematic diagram of a square lattice unit-cell with a lattice constant a. c Real part resonant frequencies in a single cavity as a function of the cavity deformation. d Energy eigenvalues in a cavity array lattice at zero crystalline momentum k = 0. In c and d, successive Demkov-type couplings for the stable regular modes and the scar modes are highlighted by thick curves. The arrows mark the degenerated scar modes (solid and dashed curves) we study.

2.12 Hierarchical zero- and one-dimensional topological states in symmetry-controllable grain boundary

Won-Jun Jang, Heeyoon Noh, Seoung-Hun Kang, Wonhee Ko, JiYeon Ku, Moon Jip Park, Hyo Won Kim

This study presents direct experimental evidence for hierarchical transitions between one-dimensional (1D) and zero-dimensional (0D) topological states at grain boundaries (GBs) in the quantum spin Hall material 1T′–$MoTe_2$. Using a scanning tunneling microscope (STM) press-and-pulse technique, the authors construct symmetry-enforced GBs with either nonsymmorphic (NonSymC2) or symmorphic (SymC2) rotational symmetry. NonSymC2 GBs preserve first-order 1D topological edge states via nonsymmorphic band degeneracy, whereas SymC2 GBs lose protection, become gapped, and realize higher-order topology through localized 0D boundary states at GB ends. This hierarchical realization demonstrates a controllable platform for symmetry-tuned topological phases.

Topological crystalline insulators and higher-order topological insulators (HOTIs) extend bulk–boundary correspondence to include states of dimension $(N-n)$, with $n>1$. Grain boundaries are particularly promising for realizing such phases, since they act as symmetry-dictated structural defects that can host boundary-localized states. In 1T′–$MoTe_2$, a known quantum spin Hall insulator, GBs naturally trap helical edge states from adjacent domains. The protection or gapping of these states depends critically on the symmetry of the GB.

The authors applied tensile strain to monolayer 1T′–$MoTe_2$ via an STM tip press-and-pulse method. This ferroelastic switching creates diamond-shaped grain variants (G1, G2, G3) with distinct Te-chain orientations. Depending on boundary matching, the GBs exhibit either NonSymC2 or SymC2 symmetry. STM/STS was then used to map local density of states (LDOS), revealing distinct spectral features associated with 1D and 0D states. Complementary tight-binding and density functional theory (DFT) calculations supported the classification and topological protection of the observed states.

NonSymC2 symmetry enforces nonsymmorphic band degeneracy that protects double-helical edge modes. STM dI/dV maps at ~ 28 mV show boundary-localized in-gap metallic states, consistent with theoretical bow-tie band crossings. Finite-length NonSymC2 GBs display quantum confinement resonances (n=1,2), further verifying the 1D boundary nature.

SymC2 GBs lose nonsymmorphic protection and develop a finite band gap. At GB ends, sharp dI/dV peaks near -4 mV reveal 0D localized states. Symmetry analysis shows equivalence to the Su–Schrieffer–Heeger (SSH) model: dimerized hoppings yield end states. Simulations confirm the higher-order classification (AIII class) of these gapped edges.

GB formation requires both mechanical strain and voltage pulses; strain alone is insufficient to stabilize switched domains. The process involves electric-field-assisted hole formation and in-plane strain transfer. Additional STM manipulation can interconvert NonSymC2 and SymC2 GBs, demonstrating tunability of the topological state type.

This work demonstrates a clear *hierarchy* of topological phases within a single material platform: First-order 1D edge states emerge at nonsymmorphic GBs. Higher-order 0D boundary states localize at symmorphic GB ends. The ability to deterministically engineer GB type and thus dimensionality of topological states provides a route to controllable HOTI realizations. This establishes grain boundaries as versatile building blocks for on-demand design of topological phases.

The STM-based manipulation of GB symmetries enables: Experimental realization of HOTI phases long predicted but rarely observed, Tailored devices combining 1D and 0D

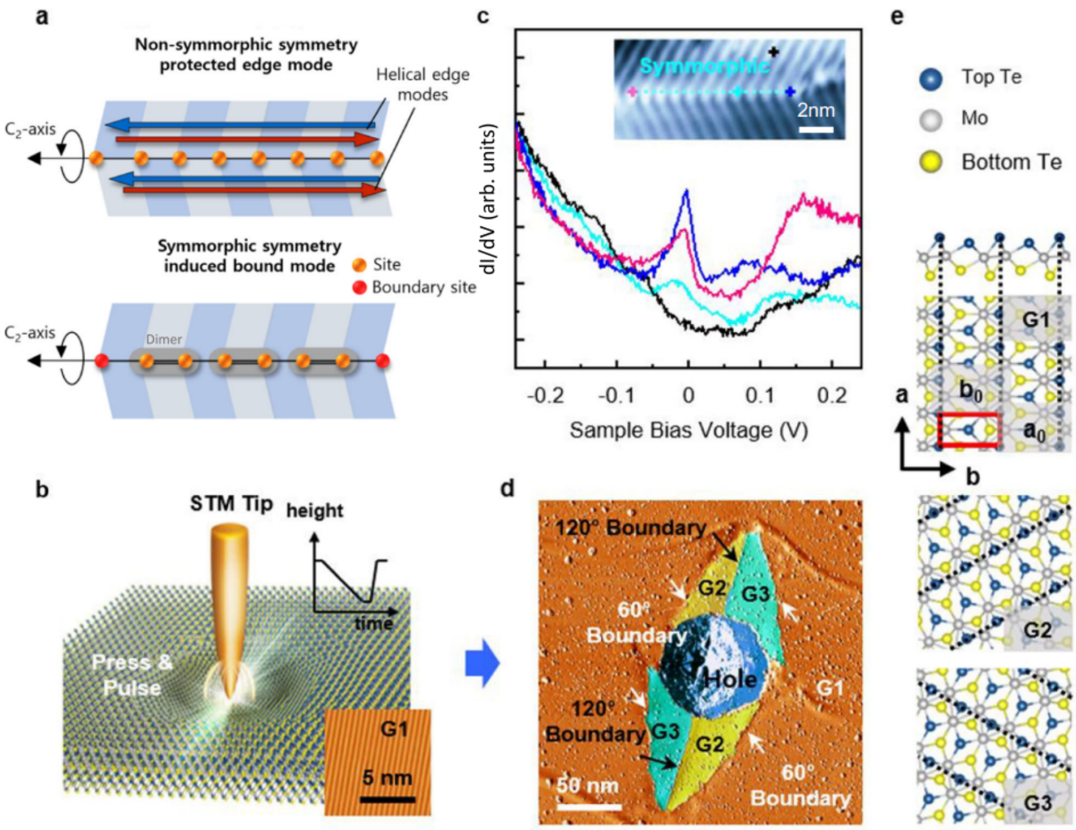

Figure 1: a Illustration of topological states in non-symmorphic and symmophic GBs. While the non-symmorphic GBs have protected edge modes, the symmorphic GBs allow atomic dimerizations, which give rise to the zero-dimensional higher-order topological states. b Schematic illustration for the GB formation process of GBs using an Scanning Tunneling Microscopy (STM) tip. Inset: Derivative STM image of pristine 1T'–MoTe2 surface showing quasi-one-dimensional chains formed by the Te atoms and denoted the region of this original chain direction as G1. c dI/dV spectra taken at the positions indicated by the black, cyan, magenta, and blue dots in the inset. Inset: STM image showing a 120° SymC2 GB created in 1T'–MoTe2. d Derivative STM image of 1T'–MoTe2 obtained after GBs formation process. e Structural models of the 1T'–MoTe2. denoted as G1, G2 and G3. The Te chain directions are marked by the dotted lines to help guide the eyes.

states for quantum transport or qubit applications, Extensions to other 2D topological materials where ferroelastic switching can be harnessed, Integration of non-Hermitian or interacting effects to further enrich the boundary-state physics.

In summary, the controllable creation of symmetry-enforced GBs in 1T′–$MoTe_2$ provides a hierarchical and tunable platform to explore and exploit topological states across dimensions.

[1] Won-Jun Jang, Heeyoon Noh, Seoung-Hun Kang, Wonhee Ko, JiYeon Ku, Moon Jip Park, Hyo Won Kim, Nature Communications 15, 9328 (2024)

2.13 Raman Peak Shift and Broadening in Crystalline Nanoparticles with Lattice Impurities

S. V. Koniakhin, O. I. Utesov, A. G. Yashenkin

This research provides a comprehensive theoretical and numerical analysis of how point-like lattice impurities affect the Raman spectra of crystalline nanoparticles, using diamond nanoparticles as a representative and technologically relevant example [1]. The study demonstrates that such disorder not only broadens the optical phonon lines but also induces a significant shift of the main Raman peak. This shift can be either a blueshift or a redshift, depending on the specific type of impurity, and is typically of the same order of magnitude as the broadening for nanometer-sized particles. The findings are crucial for the accurate interpretation of experimental Raman spectra from nanoparticle ensembles.

The Raman spectrum of a bulk crystal features a sharp peak corresponding to zone-center optical phonons. In nanoparticles, finite-size effects lead to phonon confinement and size quantization, resulting in a characteristic redshift and asymmetric broadening of this peak. The widely used Phonon Confinement Model (PCM) describes this effect phenomenologically. However, real nanoparticles also contain various lattice imperfections—such as substitutional atoms, vacancies, and nitrogen-vacancy (NV) centers in diamond—which act as additional sources of broadening and shift. This work systematically investigates these disorder-induced effects.

The methodology combines analytical techniques, based on a self-consistent T-matrix approach (SCTMA) for Bose excitations scattering off impurities, with numerical simulations using the Dynamical Matrix Method (DMM) within the Keating model for 3 nm diamond particles. The Raman intensity is calculated using the Bond Polarization Model (BPM). The analysis focuses on the highest-energy, most Raman-active optical phonon mode.

The key theoretical parameter is the disorder strength S, defined for mass disorder as $S = \langle \delta m_l^2 \rangle / m^2$. For binary disorder with a small concentration c_{imp} of impurities of mass $M = m + \delta m$, this simplifies to $S \approx c_{\text{imp}}(\delta m/m)^2$. The response of the phonon system depends on whether the levels are "separated" (weak disorder, $\Gamma \propto \sqrt{S}$) or "overlapped" (stronger disorder, $\Gamma \propto S$). The crossover occurs around $S \sim 0.005$ for 4 nm diamonds ($\Gamma \sim 1$ cm^{-1}). The overlapped regime is most relevant for typical experimental conditions.

For Gaussian disorder (random mass variations with zero mean), the analysis and simulations reveal a disorder-induced *blueshift* of the Raman peak. This is a second-order effect: the highest-frequency phonon mode shifts to higher energy by avoiding regions with heavier atoms. In the overlapped regime, the shift and broadening are proportional, related by $\delta\omega/\Gamma \approx k'_D/(2q)$, where $q \sim \pi a_0/L$ is the effective wavevector of the confined phonon. For a 3 nm diamond, this ratio is approximately 1.4, leading to the practical formula:

$$\delta\omega \approx 1.4 \cdot \left(\frac{L}{3 \text{ nm}}\right) \cdot \Gamma. \qquad (1)$$

The broadening scales as $1/L$, while the shift remains largely size-independent.

The behavior for binary disorder (a specific fraction c_{imp} of atoms replaced by a mass M) is more complex and can be divided into three regimes:

- *Weak/Heavy Impurities* ($M/m > 0.9$): Separated levels regime. A small redshift and broadening occur, with $\delta\omega \propto c_{\text{imp}}$ and $\Gamma \propto \sqrt{c_{\text{imp}}}$.
- *Non-Resonant Scattering* ($M/m < 0.9$, away from resonance): Overlapped regime. The shift and broadening follow $\delta\omega \propto c_{\text{imp}}$, $\Gamma \propto c_{\text{imp}}/L$. Their ratio is given by $\delta\omega/\Gamma = -b(u)/(2q)$, where $b(u)$ is an inverse scattering length.
- *Resonant Scattering* ($M/m \approx 0.78$): A bound state forms above the phonon

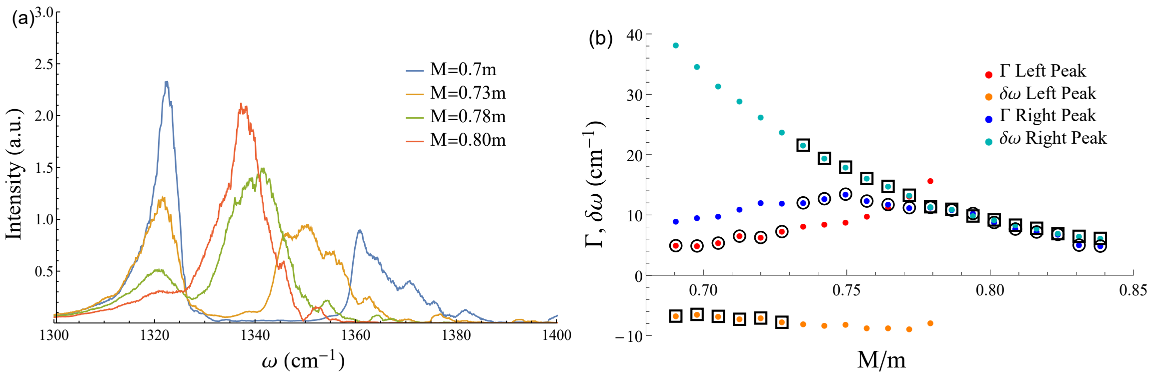

Figure 1: (a) Raman spectra of 3 nm diamond particles with 2% impurities of various masses near the resonant condition ($M/m \approx 0.78$). The spectra evolve from a single broad peak to a double-peak structure as the impurity mass decreases. (b) Broadening Γ and shift $\delta\omega$ for the dominant Raman peak as a function of impurity mass. A resonant enhancement is observed.

band. This leads to a dramatically enhanced effect, with both shift and broadening scaling as $c_{\mathrm{imp}}^{2/3}$ and becoming independent of particle size for $L \gtrsim 3$ nm. The Raman spectrum can develop a double-peak structure due to hybridized propagating and localized states (Fig. 1).

Vacancies, modeled as missing atoms, act as infinitely heavy, fixed scatterers (unitary limit). They induce a significant *redshift* and broadening. For vacancies and NV centers in diamond, the ratio is approximately constant:

$$\delta\omega \approx -1.75 \cdot \left(\frac{L}{3\ \mathrm{nm}}\right) \cdot \Gamma.$$

This redshift is explained by the additional confinement of phonons between vacancies, increasing their effective wavevector and lowering their energy. A study of NV centers (modeled as a nitrogen atom plus a vacancy with modified N-C bond strength) shows that their effect is very similar to that of simple vacancies for a wide range of plausible bond strengths, with $-\delta\omega/\Gamma \approx 1.5$.

The results lead to practical recipes for incorporating disorder effects into Raman spectrum analysis:

- For *light impurities, vacancies, and NV centers* ($c_{\mathrm{imp}} = 1-10\%$): Additional redshift $\delta\omega \approx -2.6\ \mathrm{cm}^{-1} \cdot (c_{\mathrm{imp}}/1\%)$ and broadening $\Gamma \approx 1.5\ \mathrm{cm}^{-1} \cdot (c_{\mathrm{imp}}/1\%) \cdot (3\ \mathrm{nm}/L)$.
- For *heavy impurities* ($M > 1.5m$, $c_{\mathrm{heavy}} = 1-10\%$): Saturated redshift $\delta\omega \approx -1.0\ \mathrm{cm}^{-1} \cdot (c_{\mathrm{heavy}}/1\%)$ and broadening $\Gamma \approx 0.5\ \mathrm{cm}^{-1} \cdot (c_{\mathrm{heavy}}/1\%) \cdot (3\ \mathrm{nm}/L)$.
- In resonant conditions: Both $\delta\omega$ and Γ are enhanced, scale as $c_{\mathrm{imp}}^{2/3}$, and are nearly independent of size. The shift is positive (blueshift) and proportional to the broadening.

In conclusion, lattice impurities in crystalline nanoparticles contribute significantly to both the broadening and shifting of the Raman peak. This effect must be accounted for alongside the well-known phonon confinement effect to accurately analyze experimental data. The provided simple relationships between shift and broadening, dependent on impurity type and concentration, offer a practical tool for this purpose, particularly for nanodiamonds containing NV centers or other common defects.

[1] S. V. Koniakhin, O. I. Utesov, A. G. Yashenkin, *Diamond & Related Materials* **146**, 111182 (2024)

2.14 Universal condensation threshold dependence on pump beam size for exciton-polaritons

Oleg I. Utesov, Min Park, Daegwang Choi, Soohong Choi, Suk In Park, Sooseok Kang, Jin Dong Song, Alexey N. Osipov, Alexey V. Yulin, Yong-Hoon Cho, Hyoungsoon Choi, Igor S. Aronson, Sergei V. Koniakhin

This study presents a combined experimental (KAIST Department of Physics) and theoretical (IBS Center for Theoretical Physics of Complex Systems) investigation into the fundamental process of exciton-polariton Bose-Einstein condensation (BEC) under Gaussian-shaped incoherent laser pumping [1]. We establish a universal, sample-independent law that governs the condensation threshold power as a function of the pump spot size, a crucial parameter for applications in polaritonics.

Exciton-polaritons are hybrid light-matter quasiparticles formed in semiconductor microcavities in the strong coupling regime. They can undergo Bose-Einstein condensation at relatively high temperatures, forming a macroscopic quantum state. A standard method to create such condensates is through off-resonant, incoherent pumping with a laser spot, typically Gaussian in profile. While the mean-field description of this system is well-established via the driven-dissipative Gross-Pitaevskii equation (ddGPE), the explicit relationship between the threshold pump power (P_{TH}) and the laser spot size (r_0) has remained an open question, critical for designing and controlling polariton devices.

We performed experiments on three distinct AlGaAs-based microcavity samples (KIST, KAIST 1, KAIST 2) with varying quality factors (Q $\sim$ 800 to 8400) and polariton lifetimes. For each sample, we measured the power required to achieve condensation for a wide range of Gaussian pump spot diameters (from a few to tens of microns). The condensation threshold was identified by a characteristic blueshift and non-linear increase in the emission intensity at zero in-plane momentum.

Our analytical theory tackles the near-threshold dynamics by reducing the full ddGPE for polariton wave function and rate equation for exciton reservoir density to a complex Ginzburg-Landau equation (cGLE). To obtain an analytical solution, we approximate the Gaussian pump profile with a parabolic "pseudo-potential" near its center, $P(r) = p_0 - p_1 r^2$, where $p_1 = p_0/r_0^2$, see Fig. 1. This approximation is justified as the condensate forms predominantly at the center of the pump spot. Solving the linear eigenvalue problem of the cGLE yields a Gaussian ground state mode. The condition for its growth ($\mathfrak{Re}(\lambda) = 0$) defines the threshold, leading to a central result for the dimensionless threshold power:

$$p_{\mathrm{TH}}(r_0) = \left(\frac{R_0}{r_0} + \sqrt{\frac{R_0^2}{r_0^2} + 1} \right)^2, \qquad (1)$$

where R_0 is a characteristic length scale specific to each sample.

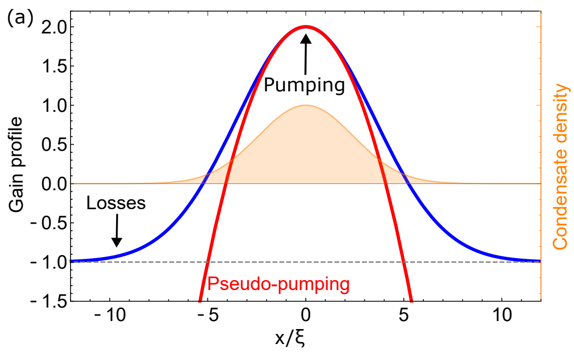

Figure 1: **Parabolic "pseudo-pumping" approximation.** Instead of considering real Gaussian pumping (blue curve), it is possible treating its small-r expansion (red parabola). Here $p_0 = 3, r_0 = 5$, and the gain accounts for polariton lifetime being $P(r) - 1$.

A profound finding is the *parameter space collapse*: the dimensionless length scale $\tilde{R}_0$ depends only on the properties of the polariton spectral line near threshold, namely the blueshift Δ, the radiative broadening $\hbar\gamma_C$, and the effective mass m:

$$\tilde{R}_0 \approx \frac{1}{\gamma_C}\sqrt{\frac{2\Delta}{m}}\mathrm{Re}\left[\left(1+\frac{i\hbar\gamma_C}{2\Delta}\right)^{1/2}\right]. \qquad (2)$$

Intrinsic sample parameters like scattering rates and interaction strengths do not appear explicitly, universalizing the dependence.

This result reveals two distinct condensation regimes governed by the ratio $r_0/\tilde{R}_0$:

- *Ballistic Regime* ($r_0 \ll \tilde{R}_0$): Polaritons gain enough kinetic energy from repulsion to ballistically escape the pump spot before decaying radiatively. The total threshold power becomes nearly independent of the spot size, $P_{\mathrm{TOT}} \sim$ constant.
- *Quasi-Homogeneous Regime* ($r_0 \gg \tilde{R}_0$): Losses are dominated by radiative decay within the condensate. The threshold power density approaches its homogeneous value, and the total power scales with the spot area, $P_{\mathrm{TOT}} \propto r_0^2$.

The consequence of the ballistic loss regime for small pump spots is the impossibility of significantly reducing the total pump power of the excitation laser by decreasing the spot size. For each sample, one has a certain minimal total laser power required to achieve the condensation $P_{\mathrm{MIN}} \sim P_{\mathrm{TH}}R_0^2$. A decrease in the spot size does not lead to a proportional reduction of the laser power. At the same time, to achieve condensation into small spots, one should pump with a laser at high power density. This physical picture, for instance, complicates the miniaturization of polariton graph simulators due to thermal management issues and reservoir density limitations.

Figure 2 shows excellent agreement between the experimental data for all three samples and the theoretical curve from Eq. (1), validating our model. The extracted $\tilde{R}_0$ values (4.22 μm, 4.62 μm, 6.95 μm for KIST, KAIST 1, KAIST 2, respectively) align with the measured blueshifts Δ and line widths, confirming the parameter space collapse.

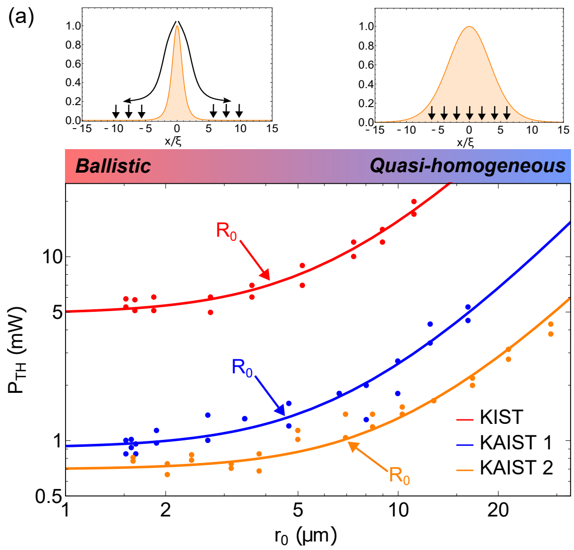

Figure 2: **Universal dependence of total threshold power on pump spot size.** Experimental data for three different samples (KIST, KAIST 1, KAIST 2) agree faithfully with the theoretical prediction (solid lines, Eq. (1)). The characteristic length $\tilde{R}_0$ for each sample, marked by arrows, separates the ballistic (left) and quasi-homogeneous (right) regimes. Insets schematically illustrate the dominant loss mechanisms.

This work provides a fundamental understanding and a practical tool for predicting the condensation threshold in a standard experimental setup. The universal law has immediate implications for the design of polaritonic devices, such as simulators and condensate lattices, where precise control over the condensation power and spot size is essential. It also establishes a method for characterizing key polariton parameters, like the loss rate γ_C, through threshold power measurements.

[1] Oleg I. Utesov, Min Park, Daegwang Choi, Soohong Choi, Suk In Park, Sooseok Kang, Jin Dong Song, Alexey N. Osipov, Alexey V. Yulin, Yong-Hoon Cho, Hyoungsoon Choi, Igor S. Aranson & Sergei V. Koniakhin, *Communications Physics* **8**, 286 (2025)

2.15 Boundary-induced Majorana coupling in a planar topological Josephson junction

H. Kim, S.-J. Choi, H.-S. Sim, and S. Park

We explores how boundary modes outside a planar Josephson junction (JJ) affect the behavior of Majorana zero modes (MZMs) hosted inside the junction. The system is formed on the surface of a three-dimensional topological insulator (3D TI) where two s-wave superconductors are deposited. While most previous studies have focused only on MZMs localized within the junction, here we investigate the indirect influence of gapless boundary channels along the edges of the superconductors and their role in lifting the degeneracy of MZMs.

The setup, illustrated in Fig. 1(a), consists of a topological JJ hosting two MZMs, γ_1 and γ_2, at the junction ends. In addition, gapless boundary modes exist in regions of the TI surface that are not covered by superconductors, or along the physical edges of a finite TI sample. For simplicity, these boundary states are represented as two chiral channels, one of which couples to the MZMs while the other remains inert. We study the effect of the boundary modes on the energy spectrum and the Josephson effect of the junction, taking into account of tunnel coupling between the MZMs and the boundary modes. We find that the coupling can give rise to an indirect route to lift the degeneracy of the states formed by the MZMs. The MZMs are hybridized into a complex fermion with a finite energy. This energy splitting is independent of the length of the boundary L_b in the weak coupling limit and for the moderate case it is much more slowly decaying with L_b than the exponential decay, with L_J, of the overlap between MZMs within the junction $\propto e^{-L_J/\xi}$ where L_J is the junction length. In the realistic situation, L_b and L_J have a similar order of magnitude, hence the effective coupling between the MZMs by the boundary modes can play an important role.

The low-energy minimal model described by the Hamiltonian $H_{\min} = H_M + H_B + H_T$, where $H_M = i\mathcal{E}\gamma_1\gamma_2$ is the Hamiltonian for the two MZMs with the coupling energy $\mathcal{E}$ due to their wave function overlap along the junction of length L_J, and $H_B = \hbar v_b k\, \eta_k^\dagger \eta_k$ is for the single chiral mode of η_k along the boundary with length L_b and velocity v_b. Using the quantization condition of the loop $kL_b+\pi = 2\pi$ with the Berry phase π originated from the spin rotation of the surface state along the round trip due to the spin-momentum locking, we find $k = \pi/L_b$. The tunnel coupling between the MZMs and the boundary mode occurring at positions s_1 and s_2 with the tunneling strengths t_1 and t_2, respectively, shown in Fig. 1(b) is given by

$$H_T = \sqrt{2}t_1\gamma_1\eta_k + \sqrt{2}t_2\gamma_2\eta_k + \text{H.c.} \quad (1)$$

The key result of our study is that this coupling gives rise to an effective coupling between the inner MZMs. It can be shown by solving the Hamiltonian in the weak tunneling limit. It is then expressed by

$$H_{\min} = iE\,\tilde{\gamma}_1\tilde{\gamma}_2, \quad (2)$$

where E is the effective coupling induced by the boundary mode,

$$E = \mathcal{E} + \frac{|t_1 + it_2|^2}{\mathcal{E} - \hbar v_b k} + \frac{|t_1 - it_2|^2}{\mathcal{E} + \hbar v_b k} + O(t^4), \quad (3)$$

For a more realistic description, the planar JJ is modeled using a two-dimensional Bogoliubov–de Gennes Hamiltonian,

$$H(\mathbf{r}) = \tau_z \left[v_F \hat{z}\cdot(\vec{\pi}\times\vec{\sigma}) - \mu(\mathbf{r})\right] + \Delta(\mathbf{r})\tau_+ + \Delta^*(\mathbf{r})\tau_-, \quad (4)$$

where $\vec{\pi} = -i\hbar\vec{\nabla} + e\vec{A}(\mathbf{r})$ includes the orbital effect of a perpendicular magnetic field. The superconducting gap $\Delta(\mathbf{r})$ is proximity-induced outside the junction region. Zeeman terms are neglected under weak magnetic fields.

Using a scattering-matrix approach, we analyze how the boundary-induced coupling modifies the energy spectrum and Josephson effect. For zero magnetic flux ($\Phi = 0$), the coupling with boundary modes removes the zero-energy degeneracy of the inner MZMs when the superconducting phase difference lies in the

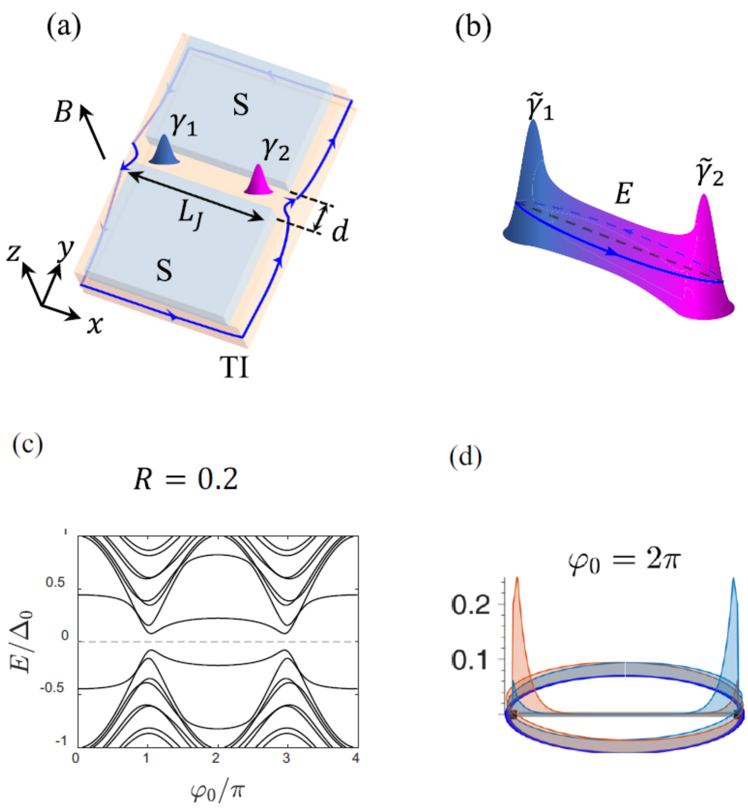

Figure 1: (a) A planar topological Josephson junction hosting two Majorana fermions, γ_1 and γ_2, which couple to boundary channels (denoted in blue). (b) Schematic of the coupling between two effective Majorana fermions, $\widetilde{\gamma_1}$ and $\widetilde{\gamma_2}$, which represent Majorana fermions modified by their coupling to the boundary channels, exhibiting inter-Majorana coupling induced by the boundary. (c) Numerical result of the energy spectrum of the Josephson junction with the boundary at $\Phi = 0$. The Majorana fermions at E=0 are lifted due to the coupling with the boundary channels. (d) Spatial probability distribution of wave functions to confirm that the energy splitting is induced via boundary channels (finite height of the amplitude along the circle).

range $\pi < \varphi_0 < 3\pi$, as shown in Fig. 1(c). The resulting energy splitting is independent of the boundary length L_b in the weak coupling regime. Furthermore, the periodicity of the Josephson spectrum evolves from 4π to 2π as the coupling strength increases. For the case of a finite flux quantum ($\Phi = \Phi_0$) within the junction, the degeneracy of the MZMs around $\varphi_0 = 3\pi$ is lifted due to the boundary-induced coupling. However, at $\varphi_0 = 2\pi$ one Majorana mode remains pinned at zero energy, since it is localized near the center of the junction and thus spatially separated from the boundary. These results highlight the nontrivial role of boundary channels, which provide a more robust mechanism for MZM hybridization than direct overlap inside the junction.

Our work demonstrates that boundary modes outside a topological Josephson junction can effectively mediate coupling between Majorana zero modes, leading to finite-energy splitting that is much less sensitive to junction size than the usual overlap mechanism. By combining analytical modeling with scattering theory, the work reveals how this effect alters the Josephson spectrum and periodicity, and clarifies the conditions under which Majorana degeneracies are lifted. The findings emphasize that realistic devices must account for such boundary-induced hybridization when designing and interpreting experiments on Majorana physics in planar JJs.

[1] H. Kim, S.-J. Choi, H.-S. Sim, and S. Park, Phys. Rev. B. **111**, 045414 (2025)

2.16 Andreev probing of a Cooper-pair flying qubit

S. Park, L. Y. Gorelik, S. I. Kulinich, H. C. Park, C. Kim, and R. I. Shekhter

We propose a superconducting device that enables the transport and probing of a superconducting qubit via nanoelectromechanics. The superconducting qubit is formed by a movable Cooper-pair box (CPB) oscillating back and forth, leading to tunneling between superconducting (s) and normal (n) electrodes. When it is in contact with the s-electrode, the qubit undergoes unitary time evolution due to the Josephson coupling, while dissipative tunneling occurs when it approaches the n-electrode, allowing us to probe the current, which depends on the qubit state. The current is nonzero at zero bias voltage, and its coherence can be identified through the oscillatory current dependence on the gate voltage. The result shows strong spatial nonlocality of the current response to the electrostatic gate potential and the proposed device provides a building block for dissipationless quantum information circuits.

A sketch of the system under consideration is shown in Fig. 1(a). It consists of s- and n-electrodes separated by a distance much greater than the tunneling length λ. A tiny superconducting island, whose position is determined by $x(t) = A \sin \omega t$, performs harmonic oscillations with amplitude A and frequency ω, periodically approaching electrodes at a distance on the order of λ. Thus, the superconducting island can have a tunnel connection with only one of the electrodes at any given time. A gate electrode, located near the central position $x = 0$, controls the electrostatic potential on the island as it passes by. We assume that the superconducting energy gap Δ (on both the island and the s-electrode) is much greater than the charging energy of the island, $E_C(x) = e^2/2C(x)$, where $C(x)$ represents the island's self-capacitance, and also greater than the energy of the Josephson connection between the island and a superconductor, $E_J(x)$. This allows us to consider the subsystem consisting of the island and the s-electrode as a two-level system - Cooper pair box, whose states are represented by a superposition of two states: $|0\rangle = (0,1)^T$ - the ground state of the neutral island, and $|1\rangle = (1,0)^T$ - the charged state of the island with two extra electrons

The Hamiltonian for the CPB, schematically shown in Fig. 1(a), is given by

$$H_{CPB} = E_J(x(t))\hat{\sigma}_1 + E_Q(x(t))\hat{\sigma}_3, \quad (1)$$

where $\hat{\sigma}_{i=1,2,3}$ are Pauli matrices acting on the qubit space spanned by two states. $E_Q(x)$ is the charging energy. When the CPB is close to the s-electrode, the Josephson coupling dominates and the coupling to the n-electrode is negligible. In that region, the qubit state evolves coherently and its density matrix $\hat{\varrho}$ undergoes unitary transformation by

$$\hat{U}_s = \rho + i\tau\hat{\sigma}_1. \quad (2)$$

The parameter, $\tau^2 = 1 - \rho^2$, carries a simple physical meaning: it represents the probability of changing the number of Cooper pairs in the island from the neutral state $|0\rangle$ to the charge state $|1\rangle$, or vice versa, as the island approaches and then moves away from the s- electrode. As the CPB moves toward the n-electrode, the coupling to the n-electrode allows the Andreev reflection. It is dissipative tunneling described by using the reduced density matrix approach:

$$\frac{d\hat{\varrho}(t)}{dt} = -i\frac{1}{\hbar}[H_{CPB}, \hat{\varrho}(t)] - \check{\hat{\mathfrak{L}}}(\hat{\varrho}), \quad (3)$$
$$\check{\hat{\mathfrak{L}}}(\hat{\varrho}) = \gamma(t)\left(\hat{\varrho}(t) + \frac{1}{2}\hat{\sigma}_3\{\hat{\sigma}_3, \hat{\varrho}\} - \hat{\sigma}_3\right),$$

where the position-dependent tunneling amplitude $\gamma(t) = \Gamma \exp\{-4A(1 + \sin \omega t)/\lambda\}$ and $\Gamma = 2\pi\hbar^{-1}t_A^2\nu^2|E_Q^{(n)}|$, with $E_Q^{(n)} = E_Q(-A) - e\Delta V$, where ΔV is the voltage difference between the electrodes, and ν is the electronic density of states. In the limit $\Gamma \ll \omega$, the average current, shown in Fig. 1(c), flowing through the CPB can be expressed as

$$I = I_A \frac{\tau^2}{\tau^2 + 2(1-\tau^2)\sin^2 \Phi}, \quad (4)$$

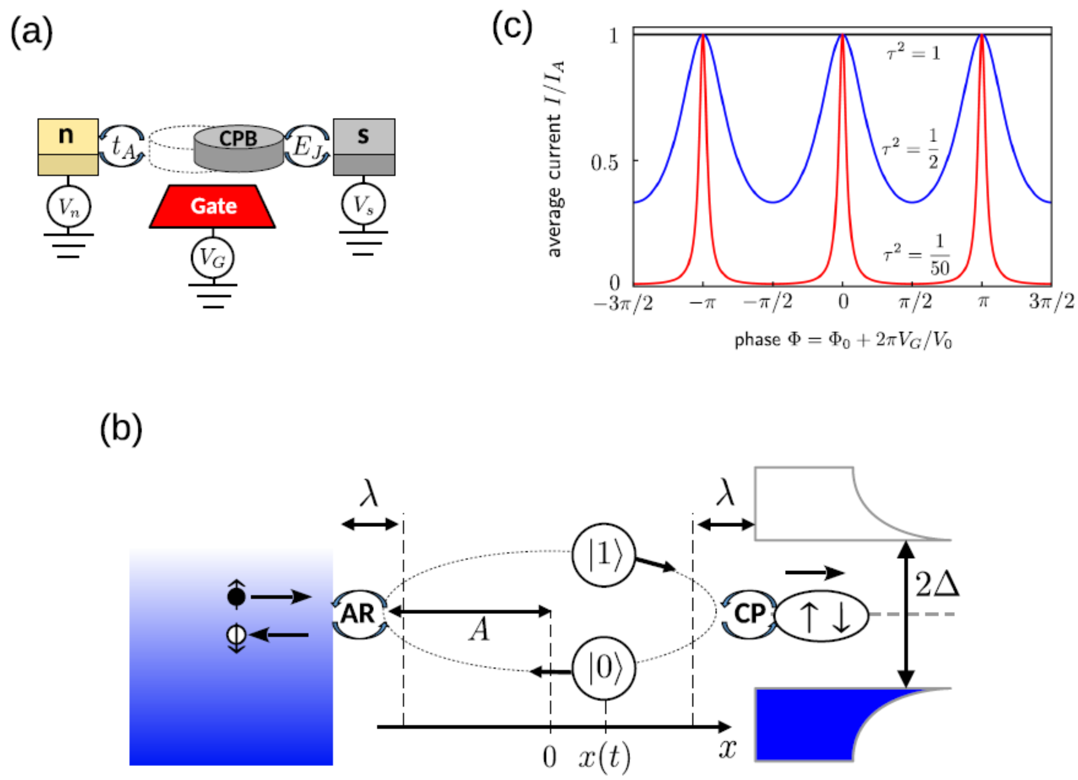

Figure 1: (a) A schematic of the nanomechanical device for the Cooper-pair flying qubit, consisting of the Cooper-pair box (CPB) which moves periodically between the s- and n-electrodes. (b) The qubit defined on the CPB is tunnel coupled with the s-electrode through the Josephson coupling, accompanying Cooper-pair tunneling (CP) and the n-electrode via Andreev reflection (AR). (c) Average current I in a stationary regime as a function of the gate voltage V_G. The peaks correspond to the constructive interference of coherent Cooper-pair pumping between the qubit and the electrodes, manifesting the coherent transfer of the CPB qubit.

where $\Phi = \Phi_0 + 2\pi V_G/V_0$ is the total phase accumulated along the trajectory between the electrodes. Note that V_G and A are adjustable parameters, which can be tuned to achieve a desired qubit state. By knowing these parameters and measuring the average current, one can detect the state of the qubit.

The results in Eq. (4) in our analysis present the electrical current via the nanomechanical pumping of Cooper pairs. It presents the electrical current through the device as a result of nanomechanical pumping of Cooper pairs. As such, the finite current exists even in the absence of the bias voltage. Such a pumping is attributed to the followings. One is the stochastic and noncoherent tunnel coupling of the CPB with a normal metal reservoir. Such perturbation serves as a source of dissipation constraining the life time of the flying qubit. It is a typical element for a classical pumping device. Another perturbation shifted in time as compared to the first one is the scattering of two level qubit states under the tunnel coupling with superconductor. Such scattering involves quantum states on the CPB and BCS state in the the quantum evolution and represents the perturbation typical for quantum pumping. As a result current flow through our device should be viewed as an interplay of classical and quantum pumping elements. As a consequence, dissipationfull phenomenon is still dependent on quantum mechanical phase resulting in mechanically assisted Andreev current.

[1] S. Park, L. Y. Gorelik, S. I. Kulinich, H. C. Park, C. Kim, and R. I. Shekhter, Phys. Rev. B **111**, 165403 (2025)

2.17 Fermi arc reconstruction in synthetic photonic lattice

D.-H.-Minh Nguyen, Chiara Devescovi, Dung Xuan Nguyen, Hai Son Nguyen, Dario Bercioux

Weyl semimetals (WSMs) are three-dimensional topological phases characterized by pairs of Weyl nodes—linear band touching points that act as monopoles of Berry curvature in momentum space. Their hallmark surface states are open Fermi surfaces known as Fermi arcs, which connect Weyl nodes of opposite chirality and reflect the nontrivial topology of the bulk bands. A long-standing prediction is that when two different Weyl semimetals meet at an interface, their Fermi arcs can hybridize and undergo a reconstruction that changes their connectivity. Observation of such reconstruction has been elusive in solid-state materials, where disorder and surface imperfections hinder direct measurements. In this work, we present the first direct realization of Fermi arc reconstruction in a synthetic photonic lattice, where the geometry of light in dielectric gratings emulates the band topology of WSMs.

The physical platform, showed in Fig 1 **(a)**, is a slab waveguide consisting of three dielectric gratings with identical subwavelength period Λ. Each grating layer supports two counterpropagating guided modes along the x-axis. Coupling between these modes arises from two mechanisms: (a) Intralayer diffraction coupling with amplitude U_ℓ in layer ℓ, (b) Interlayer evanescent coupling with rates V_j between adjacent layers. Collecting the six modes into a vector $\Psi = (\psi_1, \ldots, \psi_6)$, the system is governed by a 6×6 effective Hamiltonian of block-tridiagonal form:

$$H(k, \delta_1, \delta_2) = \begin{pmatrix} \Delta_1 & \Omega_1 & 0 \\ \Omega_1^\dagger & \Delta_2 & \Omega_2 \\ 0 & \Omega_2^\dagger & \Delta_3 \end{pmatrix}, \qquad (1)$$

where $\Delta_l = \omega_{0l} + \begin{pmatrix} v_l k & U_l \\ U_l & -v_l k \end{pmatrix}$ represents the guided modes in layer l with their intrlayer coupling, and $\Omega_j = \begin{pmatrix} V_j e^{-i\pi\delta_j/\Lambda} & 0 \\ 0 & V_j e^{i\pi\delta_j/\Lambda} \end{pmatrix}$ indicates the interlayer coupling. The phases depend on the relative shift δ_j between gratings. Since a shift $\delta_j \to \delta_j + \Lambda$ leaves the structure invariant, the displacements define synthetic momenta:

$$q_j = 2\pi \frac{\delta_j}{\Lambda^2}. \qquad (2)$$

Thus the trilayer system realizes an artificial three-dimensional momentum space (k, q_1, q_2), which acts as a synthetic Brillouin zone. The effective Hamiltonian can then be expanded around band crossings to yield a Weyl Hamiltonian of the form

$$H_{Weyl} = \sum_i v_i q_i \sigma_i \qquad (3)$$

with Pauli matrices σ_i acting in the two-mode subspace and velocities v_i determined by the coupling constants. By tuning the coupling parameters (U_ℓ, V_j), we map out the possible topological phases of the system.

When two Weyl nodes of opposite chirality annihilate, the system transitions into a 3D Chern insulator, where each two-dimensional slice perpendicular to q_z carries a quantized Chern number. This was verified by numerical integration of the Berry curvature:

$$C(k) = \frac{1}{2\pi} \int_{BZ} dq_1 dq_2 F_{q_1,q_2}(k, q, q_2) \qquad (4)$$

In another regime, the band crossing extends into loops, producing a nodal-line semimetal characterized by a π Berry phase accumulated around the loop. FDTD simulations of the dielectric structure reproduced these phases, confirming the validity of the effective Hamiltonian.

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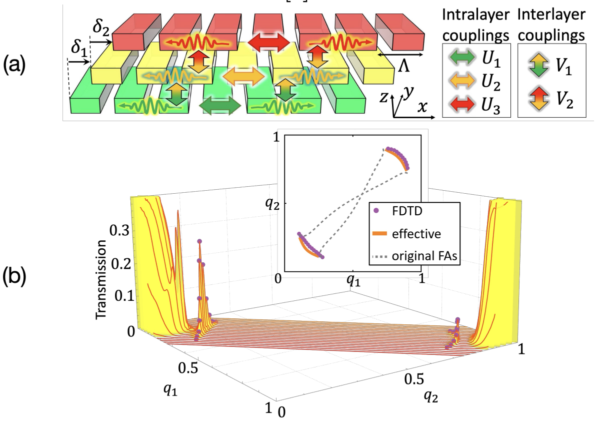

Figure 1: **(a)** Sketch of a 1D trilayer photonic grating with period Λ. The relative displacements between adjacent layers are denoted by δ_1 and δ_2. The optical guided modes of interest couple with each other via intralayer diffraction and interlayer evanescent field, described by the coupling rates U_l and V_j, respectively. **(b)** The dashed lines indicate the frequencies for visualizing the isofrequency transmission over the synthetic BZ. The inset shows the reconstructed FAs, with the dashed gray lines being the FAs before reconstruction.

We also demonstrate the Fermi arc reconstruction at the interface of two distinct WSM configurations, demonstrated in Fig 1 (b). Consider two trilayer gratings with relative displacements δ_j chosen such that their Weyl nodes are related by reflection. Placing them side by side creates a domain wall between two WSM phases. At this junction, the surface Fermi arcs do not remain confined to their respective sides; instead, they hybridize and reorganize.

The reconstructed arcs no longer connect Weyl nodes of opposite chirality within a single bulk but instead join Weyl nodes across the interface. Isofrequency contours of the surface spectrum display arcs that bend and anti-cross, clear evidence of hybridization. Finite-difference time-domain simulations confirmed the presence of these interface-localized states and matched the predictions of the effective model. In this way, we provide the first direct visualization of Fermi arc reconstruction, a phenomenon previously restricted to theoretical proposals.

The trilayer photonic lattice can be fabricated in silicon at telecommunication wavelengths with a period $\Lambda \sim 380,\text{nm}$ using electron-beam lithography and dry etching. Relative displacements δ_j, which control the synthetic momenta, can be fixed during fabrication or dynamically tuned with piezoelectric actuators. Fermi arc states could be probed via far-field spectroscopy, near-field optical mapping, or by coupling to embedded quantum emitters.

The reconstructed arcs are topologically protected boundary channels, robust to fabrication disorder. They provide a promising platform for designing photonic devices that exploit unidirectional transport, such as topological nanolasers, protected optical waveguides, and quantum interfaces.

In summary, we have constructed a synthetic photonic lattice that realizes Weyl semimetals, Chern insulators, and nodal-line semimetals in a unified platform. By introducing synthetic momenta from relative grating displacements, we engineered and controlled the motion of Weyl points in a three-dimensional Brillouin zone. At the interface between two WSMs, we demonstrated the long-predicted phenomenon of Fermi arc reconstruction, where the connectivity of surface arcs changes due to hybridization across the junction. Our work establishes synthetic photonic lattices as a versatile simulator for higher-dimensional topological physics and provides the first experimental proposal of reconstructed Fermi arcs. Beyond its conceptual importance, the platform opens opportunities for robust quantum photonic devices in which topological protection and engineered interfaces are combined for light–matter interactions and information processing.

[1] D.-H.-Minh Nguyen, Chiara Devescovi, Dung Xuan Nguyen, Hai Son Nguyen, Dario Bercioux, "Fermi arc reconstruction in synthetic photonic lattice", Physical Review Letters, 131, 053602 (2023)

2.18 Noncommutative field theory of the Tkachenko mode: Symmetries and decay rate

Yi-Hsien Du, Sergej Moroz, Dung Xuan Nguyen, Dam Thanh Son

The Tkachenko mode is the collective oscillation of vortex lattices formed in rotating superfluids such as Bose–Einstein condensates (BECs). Unlike conventional phonons, Tkachenko modes display a quadratic dispersion relation at small momentum, $\omega \sim q^2$, and only a single polarization. They emerge as the unique Nambu–Goldstone boson of a system in which both particle number and translational symmetries are spontaneously broken by the presence of a vortex lattice. Despite their importance, a systematic effective field theory (EFT) description of Tkachenko modes, particularly one that accounts for interaction effects and decay processes, has remained incomplete. We develop such an EFT, showing that the Tkachenko field is naturally understood as a compact noncommutative Nambu–Goldstone boson. The framework not only clarifies the symmetry structure of the system but also provides quantitative predictions for the decay width of the mode at zero and finite temperature.

Rotating a superfluid is formally equivalent to subjecting bosons to a magnetic field. In the lowest Landau level (LLL), guiding-center coordinates become noncommutative, obeying

$$[\hat{x}, \hat{y}] = i\theta, \quad \theta = -\ell_B^2, \quad \ell_B = \frac{1}{\sqrt{B}}, \qquad (1)$$

where B is the effective magnetic field proportional to the angular velocity of rotation.

The vortex lattice may be described by two scalar fields X^a ($a = 1, 2$), which represent frozen coordinates of the solid, as demonstrated in Fig 1. Their dynamics are constrained by an area-preserving condition,

$$\frac{1}{2}\epsilon_{ab}\,\epsilon^{ij}\partial_i X^a \partial_j X^b = 1. \qquad (2)$$

This ensures that vortex displacements correspond to incompressible, divergence-free deformations. To satisfy this constraint, the fields X^a are expressed in terms of a compact scalar ϕ through

$$X^a = x^a + \theta\epsilon^{ab} D_b\phi, \qquad (3)$$

with $U = e^{i\phi}$ and $D_i\phi = -i\partial_i U \star U^{-1}$,and $\star$ is the Moyal product. In this representation, the Tkachenko field ϕ plays a dual role: it is simultaneously the phase of the superfluid condensate and the displacement field of the vortex lattice. This duality arises because at low energies the condensate phase is determined entirely by the vortex configuration, once singular vortex contributions are subtracted.

The noncommutativity of the LLL also manifests in the algebra of magnetic translations:

$$[\hat{P}_x, \hat{P}_y] = -\frac{i}{\theta}\hat{Q}, \qquad (4)$$

where $\hat{Q}$ is the U(1) particle number operator. Acting on the Tkachenko field, magnetic translations shift ϕ by terms proportional to linear functions of position, as well as higher-derivative corrections. At leading order, this reproduces a dipole symmetry transformation, $\phi \to \phi + \alpha_i x^i$, but the full transformation includes an infinite tower of derivative terms, making the symmetry non-Abelian.

Thus, magnetic translations in this system realize a **noncommutative version of dipole symmetry**, a structure recently studied in fracton physics and higher-rank gauge theories. Importantly, this symmetry protects the quadratic dispersion relation of Tkachenko modes and organizes the EFT in terms of invariant building blocks.

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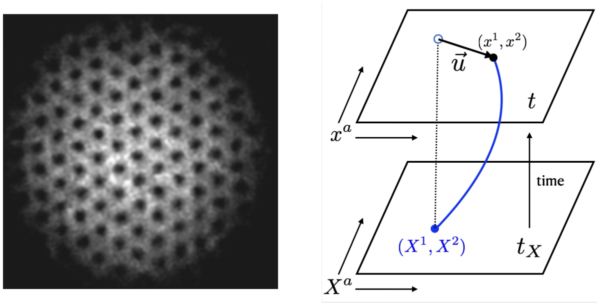

(a) (b)

Figure 1: **(a)** The vortex lattice in BEC of ^{87}Rb. **(b)** The cartesian coordinates X^1 and X^2 label vortices at the initial time t_X . These coordinates are frozen into the vortex system and thus are fixed along each vortex (blue) worldline during time evolution. The displacement $u_a(t, x^i) = x^a - X^a(t, x^i)$.

With the symmetry principles established, the authors construct the most general Lagrangian for the Tkachenko field. The relevant invariants are $D_t\phi$ and $D_{ab}\phi$, where the latter is symmetric and traceless. Expanding in derivatives, the quadratic effective Lagrangian takes the form of the quantum Lifshitz model:

$$\mathcal{L}_2 = \frac{c_0}{2}(\partial_t\phi)^2 - \frac{c_1}{2}(\nabla^2\phi)^2, \tag{5}$$

leading directly to the quadratic dispersion relation

$$\omega \sim q^2. \tag{6}$$

The dispersion is robust, being enforced by magnetic translation symmetry. Moreover, the construction realizes the celebrated Girvin–MacDonald–Platzman (GMP) algebra of the fractional quantum Hall effect, further underscoring the connection between vortex lattices and noncommutative field theory.

Beyond quadratic order, interaction terms arise. The cubic effective Lagrangian contains terms such as

$$\mathcal{L}_3 = g_1(\partial_t\phi)^3 + g_2(\partial_t\phi)(\nabla^2\phi)^2 + g_3\,\mathrm{Im}(\partial_z^2\phi)^3. \tag{7}$$

These terms allow one Tkachenko quantum to decay into two, a process kinematically permitted due to the quadratic dispersion. Evaluating the decay amplitude, we show that at zero temperature the decay width scales as

$$\Gamma(E) \sim g^2E^3. \tag{8}$$

Crucially, the ratio $\Gamma/E \to 0$ as $E \to 0$, meaning that the Tkachenko mode becomes increasingly sharp and well-defined at low energies. This result contrasts with earlier microscopic calculations, which predicted an energy-independent width-to-energy ratio, and highlights the importance of enforcing symmetry principles at the EFT level.

At finite temperature, additional processes contribute, most notably Landau damping, where a soft Tkachenko quantum is absorbed by a thermal excitation. In this regime, the width scales as

$$\Gamma(E) \sim g^2(TE)^{3/2}, \quad g^2T^3 \ll E \ll T, \tag{9}$$

so the mode remains long-lived except in the deep hydrodynamic limit $E \ll g^2T^3$. This reinforces the robustness of Tkachenko oscillations as genuine quasiparticles even at nonzero temperature.

In conclusion, we present the first systematic noncommutative field theory of the Tkachenko mode, unifying vortex lattice physics with the broader framework of noncommutative geometry and dipole symmetries. By recognizing the Tkachenko field as a compact noncommutative Nambu–Goldstone boson, we resolve the nonlinear structure of the vortex lattice and construct an EFT constrained by magnetic translations. The resulting theory reproduces the quadratic dispersion, realizes the GMP algebra, and predicts a decay width $\Gamma \sim E^3$ at zero temperature, with controlled modifications at finite temperature.

We demonstrate that Tkachenko modes are increasingly well-defined quasiparticles at low energies, contrary to earlier expectations of strong damping. This provides a robust theoretical foundation for interpreting Tkachenko oscillations observed in cold atom experiments and potentially in neutron stars, and opens the way for further applications of noncommutative field theory to strongly correlated rotating superfluids and quantum melting transitions of vortex crystals.

[1] Yi-Hsien Du, Sergej Moroz, Dung Xuan Nguyen, Dam Thanh Son, “Noncommutative Field Theory of the Tkachenko Mode: Symmetries and Decay Rate.” Physical Review Research, 6, L012040 (2024)

2.19 Work Extraction from Unknown Quantum Sources

Dominik Šafránek, Dario Rosa, and Felix C. Binder

We derive the quantifiers of maximally extractable work [1] under the following operational constrains: the initial state can be pure or mixed but is completely unknown, however, we have access to its infinitely many copies. Second, it is possible to perform a single type of coarse projective measurement on these copies. Third, given the information from this measurement, it is allowed to apply any unitary on these states. We dub them Boltzmann and observational ergotropy, because they are implicitly defined by the average Boltzmann and observational entropy, respectively. The first applies to a situation when the measurement outcomes are employed in the work extraction process, the second when the partially characterized source is no longer measured. Finally, we illustrate the effects of the operational constraints on work extraction from an evolving quantum state.

The work extraction protocol consists of two unitary operations: First, a random unitary $\bigoplus_i \tilde{U}_i$ that randomizes states in each macrostate-subspace related to a single measurement outcome is applied. This is necessary to make the task tractable, by making the average state effectively known. Then a non-random global extraction unitary U, which makes use of the partial information, is applied to extract the remaining available energy. Thus, the total extraction operation, which is partially random, is

$$U \bigoplus_i \tilde{U}_i. \tag{1}$$

Unitary U acts on the entire Hilbert space, and it is later optimized to take into account the knowledge of either outcomes i or probabilities p_i obtained from the measurements. $\tilde{U}_i$ are random unitaries, each acting on the corresponding macrostate-subspace $\mathcal{H}_i$. We choose operations $\tilde{U}_i$ to be completely random, according to the Haar measure. This ensures that averaging over many realizations of the protocol leads to the following mathematical formula, defining a non-unitary operation

$$\begin{aligned}\mathcal{U}(\rho) &= U\Big(\int (\bigoplus_i \tilde{U}_i)\rho(\bigoplus_i \tilde{U}_i^\dagger)d\mu(\bigoplus_i \tilde{U}_i)\Big)U^\dagger \\ &= U\rho_{\mathrm{cg}}U^\dagger.\end{aligned} \tag{2}$$

Here, the coarse-grained state

$$\rho_{\mathrm{cg}} = \sum_i \frac{p_i}{V_i} P_i \tag{3}$$

is known, because both p_i and V_i are experimentally available, unlike the full original state ρ. $V_i = \mathrm{tr}[P_i] = \dim \mathcal{H}_i$ is the volume of the macrostate (the number of its constituent distinct microstates), which depends solely on the measurement. $\mathcal{C} = \{P_i\}$ represents the projectors of a coarse projective measurement.

In the case of simultaneous extraction from N copies of the initial state, we derive the *Boltzmann ergotropy in the large-N limit*,

$$W_{\mathcal{C}}^{B\infty}(\rho) = \mathrm{tr}[H(\rho - \rho_\beta)]. \tag{4}$$

Temperature of the thermal state $\rho_\beta = e^{-\beta H}/Z$ is implicitly defined by requiring that its von Neumann entropy equals the mean *Boltzmann entropy* with coarse-graining $\mathcal{C}$,

$$S_{\mathrm{vN}}(\rho_\beta) = S_{\mathcal{C}}^B. \tag{5}$$

The mean Boltzmann entropy is defined as $S_{\mathcal{C}}^B = \sum_i p_i \ln V_i$, in which both p_i and V_i are experimentally accessible.

In the case of simultaneous extraction from N copies of the initial state without any further measurements, we obtain the *observational ergotropy in the large-N limit*,

$$W_{\mathcal{C}}^{\infty}(\rho) = \mathrm{tr}[H(\rho - \rho_{\beta'})]. \tag{6}$$

Temperature β' of the thermal state is implicitly defined by requiring that its von Neumann entropy equals the observational entropy,

$$S_{\mathrm{vN}}(\rho_{\beta'}) = S_{\mathcal{C}}. \tag{7}$$

Observational entropy is the sum of Shannon and mean Boltzmann entropy, $S_{\mathcal{C}} = S_{\mathcal{C}}^{Sh} + S_{\mathcal{C}}^B =$

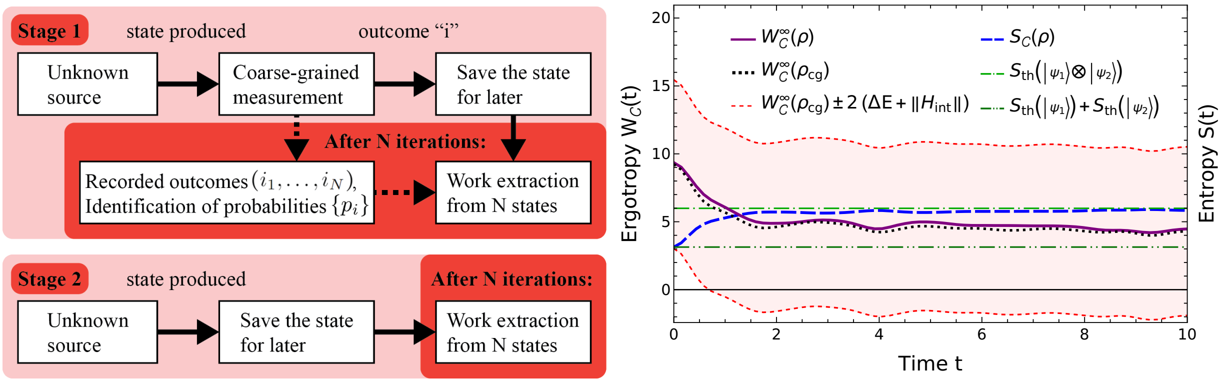

Figure 2: Left: Scheme of work extraction from unknown sources.
Right: Observational ergotropy and observational entropy as a function of time, for a thermalizing system of four particles. Here, $\mathcal{C}$ is chosen to be a local energy coarse-graining; the initial state $|\psi_1\rangle \otimes |\psi_2\rangle$, $|\psi_1\rangle = |000000\rangle$ and $|\psi_2\rangle = |111100\rangle$, evolves with the Hamiltonian given by Eq. (8), with $T = V = 1$ and $T' = V' = 0.96$. We choose the energy resolution $\Delta E = (E_1 - E_0)/2$, where E_0 and E_1 are the ground and first excited state energy, respectively. True ergotropy $W_{\mathcal{C}}^{\infty}(\rho)$ (solid purple) is unknown to the experimenter. However, they can estimate the value of $W_{\mathcal{C}}^{\infty}(\rho_{\rm cg})$ (red dotted), $\rho_{\rm cg} = \sum_{E_1,E_2} \frac{p_{E_1E_2}(t)}{V_{E_1}V_{E_2}} P_{E_1} \otimes P_{E_2}$, and be sure that the true value lies within the light-red shaded region, between the red-dashed lines representing $W_{\mathcal{C}}^{\infty}(\rho_{\rm cg}) \pm 2(||H_{\rm int}|| + \Delta E)$. We compare this with observational entropy $S_{\mathcal{C}}(\rho)$ (blue long-dashed) called non-equilibrium thermodynamic entropy for this particular coarse-graining. It is bounded by the sum of initial thermodynamic entropies (dark green dot-dot-dashed) and by the final thermodynamic entropy (green dot-dashed), $S_{\rm th} \equiv S_{C_E}$, defined as observational entropy with global energy coarse-graining with the same resolution ΔE. Observational ergotropy is directly defined by observational entropy, and inversely related to it, as per Eqs. (6) and (7).

$-\sum_i p_i \ln p_i + \sum_i p_i \ln V_i$. Eq. (6) measures the average amount of extractable work per copy when extracting simultaneously from a large number of copies of the state, produced by the source characterized solely by the probabilities $\{p_i\}$.

We illustrate the essence of our result by examining observational ergotropy as a function of time for a thermalizing system. We assume that we can measure local energies. We consider a widely-used and generic one-dimensional fermionic Hamiltonian, with the nearest neighbor and next-nearest neighbor interaction, describing interacting particles hopping between k'th and l'th site as

$$H^{(k:l)} = \sum_{i=k}^{l} -T f_i^\dagger f_{i+1} - T' f_i^\dagger f_{i+2} + h.c. + V n_i n_{i+1} + V' n_i n_{i+2}. \quad (8)$$

In summary, assuming that a source of unknown states can be characterized only by a single type of coarse-grained measurement, we designed the extraction protocol as follows. A random unitary is applied on each measurement subspace. Then we apply a global unitary operation that optimizes the energy extraction by taking the knowledge obtained from the measurement into account. Because of the randomness, also the work extracted is random. However, because the unitaries were picked with the Haar measure, the extracted work average is computable. This allows to determine the work output of the source.

[1] Dominik Šafránek, Dario Rosa, and Felix C. Binder, Phys. Rev. Lett. 130, 210401 (2023).

2.20 Observational entropy with general quantum priors

Ge Bai, Dominik Šafránek, Joseph Schindler, Francesco Buscemi, and Valerio Scarani

We derive the quantifiers of maximally extractable work under the following operational constrains [1]: the initial state can be we explore possible generalizations of OE. We note that the original OE includes an implicit prior belief about the state, which is the uniform distribution. Since in several applications the uniform prior cannot be used, e.g., in infinite-dimensional or continuous variable systems, or does not play well with other physical constraints, e.g., in thermodynamic systems with a nondegenerate Hamiltonian at finite temperature, we allow the observer to have a non-uniform prior. More generally, we consider the possibility that the observer has a reference prior described by an arbitrary density operator, which may not even commute with the state of the system. In this case, classical probability distributions may not be sufficient to describe the non-commutativity between the state and the reference, and thus the original definition of OE is not applicable.

In what follows, we restrict our attention to finite-dimensional quantum systems, with Hilbert space $\mathbb{C}^d$, and finite measurements, i.e., positive operator-valued measures (POVMs) $\mathsf{M} = \{\Pi_y\}_y$ labeled by the elements of a finite set $y \in \{1, \ldots, m\}$. In this context, the definition of OE is

$$S_{\mathsf{M}}(\rho) := -\sum_{y=1}^{m} p_y \ln \frac{p_y}{V_y}\,, \tag{1}$$

where $p_y := \mathrm{tr}\rho\Pi_y$ and $V_y := \mathrm{tr}\Pi_y$. One of the conceptual advantages of OE is that it is able to "interpolate" between Boltzmann and Gibbs–Shannon entropies. On the one hand, if the measurement is so coarse-grained that one of its elements (say Π_1) is the projector on the support of ρ, then $S_{\mathsf{M}}(\rho) = \ln V_1$ takes the form of a Boltzmann entropy. If, on the other hand, the measurement is projective and rank-one (i.e., $V_y = 1$ for all y), then $S_{\mathsf{M}}(\rho)$ coincides with the Shannon entropy of the probability distribution $\{p_y\}$, which is equal to $S(\rho)$ when $\rho = \sum_y p_y \Pi_y$.

In general, it holds that

$$\Sigma_{\mathsf{M}}(\rho) := S_{\mathsf{M}}(\rho) - S(\rho) \geq 0\,. \tag{2}$$

If $S(\rho)$ represents, in von Neumann's original narrative, the *least* uncertainty that an observer, able to perform *any* measurement in principle allowed by quantum theory, has about the state of the system, then the additional uncertainty $\Sigma_{\mathsf{M}}(\rho)$ included in OE is a consequence of observing the system through the "lens" provided by the given measurement M. Thus, in this sense, OE can be seen as a measure of how inadequate a given measurement M is with respect to the state ρ.

There exists evocative re-writing of (2), which in turn suggests that further structures may play a role in the definition of OE. Specifically, here we exhibit a *dynamical* interpretation of OE, based on a measurement process defined as follows.

Let $\rho = \sum_{x=1}^{d} \lambda_x |\psi_x\rangle\langle\psi_x|$ be a diagonal decomposition of the state of the system. We consider a stochastic map associated to a prepare-and-measure protocol: with probability λ_x, the state $|\psi_x\rangle$ is prepared, and it is then measured with the POVM $\mathsf{M} = \{\Pi_y\}_y$, yielding outcome y with a probability given by the Born rule, that is

$$P_F(y|x) := \langle\psi_x|\Pi_y|\psi_x\rangle\,, \tag{3}$$

$$P_F(x,y) := \lambda_x\langle\psi_x|\Pi_y|\psi_x\rangle\,. \tag{4}$$

The subscript F stands for "forward". This is because, as we will see in what follows, the quantity $\Sigma_{\mathsf{M}}(\rho)$ in (2) emerges also from a comparison between the forward map defined above and a suitably defined "reverse" map.

The retrodictive probability is defined as

$$P_R^u(y,x) = p_y\langle\psi_x|\frac{\Pi_y}{\mathrm{tr}\Pi_y}|\psi_x\rangle\,. \tag{5}$$

The above can also be read as a prepare-and-measure process, in which the state $\sigma_y := \frac{\Pi_y}{\mathrm{tr}\Pi_y}$

Definition	Deficiency interpretation	Irretrodictability interpretation	Equal to $S^{\text{clax}}_{\mathsf{M},\gamma}(\rho)$ when	Petz recovery criterion	Non-decreasing under stochastic post-processing
$S^{(1)}_{\mathsf{M},\gamma}$	$D(\rho\\|\gamma) - D(\mathcal{M}(\rho)\\|\mathcal{M}(\gamma))$	N/A	$[\rho,\gamma]=0$	Yes	Yes
$S^{(2)}_{\mathsf{M},\gamma}$	N/A	$D(Q_F\\|Q^{\gamma}_R)$	ρ,γ,Π_y commute	Yes	No
$S^{(3)}_{\mathsf{M},\gamma}$	$D_{\text{BS}}(\rho\\|\gamma) - D(\mathcal{M}(\rho)\\|\mathcal{M}(\gamma))$	$D_{\text{BS}}({}^tQ_F\\|{}^tQ^{\gamma}_R)$	$[\rho,\gamma]=0$	Yes	Yes

Table 1: Properties of $S^{(j)}_{\mathsf{M},\gamma}$. The expressions for the statistical deficiency and irretrodictability interpretations do not match if one uses the Umegaki relative entropy. On the other hand, the use of the Belavkin-Staszewski relative entropy gives an expression that unifies both interpretations.

is prepared with probability p_y, and later measured in the basis $\{|\psi_x\rangle\}$. The process in (5) is the process that a retrodictive agent would infer, knowing only the forward process (4) and the outcome distribution p_y, but completely ignoring the actual distribution λ_x, so that the latter is replaced by the uniform distribution.

Using (4) and (5), it is straightforward to check that

$$\Sigma_{\mathsf{M}}(\rho) = D(P_F\|P^u_R)\ . \qquad (6)$$

The above relation suggests an alternative interpretation for the difference $\Sigma_{\mathsf{M}}(\rho)$, as the degree of statistical distinguishability between a predictive process.

Further, we propose some candidates for OE with a general reference prior state. One arising from the statistical deficiency approach, is the difference between relative entropies evaluated on the input system and the output system; one arising from the irretrodictability approach, is the relative entropy between the forward and reverse processes, and one that take either or both of these forms. These definitions and their properties are summarized in Table 1.

The original definition [Eq. (1)] of observational entropy (OE) was known to be lower-bounded by the von Neumann entropy. Here we have first brought to the fore that the excess term $\Sigma_{\mathsf{M}}(\rho)$ can be interpreted in two ways: as a statistical deficiency, quantifying the decrease of state distinguishability induced by the measurement; and as irretrodictability, quantifying the hardness of retrodicting the input from the output statistics. While it is intuitive that recovering the input state is harder if the measurement makes states less distinguishable, the exact coincidence of the quantifiers is of interest.

In both interpretations, we observe that the uniform state u plays the role of reference, or prior, knowledge. This may not represent the proper knowledge of the physical situation: for instance, for systems in contact with a thermal bath, it may be more natural to choose the Gibbs prior. Based on this, we have studied generalisations of OE, in which the prior knowledge can be an arbitrary state γ.

When $[\rho,\gamma]=0$, we find an obvious generalisation of the excess term that retains both interpretations of statistical deficiency and irretrodictability. This is no longer straightforward for a general quantum prior. Technically, one of the main difficulty lies in that the irretrodictability quantifier is a relative entropy between joint input-and-output objects, whose definition in quantum theory is a current topic of research. We have explored three possible definitions of generalized OE (Table 1): two specifically designed to satisfy one of the interpretations but lacking the other; the third retaining both by replacing the usual Umegaki relative entropy with the Belavkin-Staszewski version. Thus we have a novel fully quantum object, that quantifies simultaneously the loss of distinguishability by the measurement and the hardness to retrodict the input knowing the output. Being built from information-theoretical considerations, our new formulation of OE may also hold significance in physical (thermodynamical) contexts.

[1] Ge Bai, Dominik Šafránek, Joseph Schindler, Francesco Buscemi, and Valerio Scarani, Quantum 8, 1524 (2024)

2.21 Pumping and cooling of the nanomechanical vibrations generated by the Cooper pairs exchange

A. V. Parafilo, L. Y. Gorelik, H. C. Park, R. I. Shekhter

Nanoelectromechanical (NEM) systems provide a promising platform for studying the interplay between mechanical motion and electronic transport at the quantum level. In particular, carbon nanotube (CNT) resonators coupled to electronic leads can exhibit self-driven oscillations and cooling effects, making them attractive for mass and force sensing, as well as for quantum technologies. When superconducting (SC) elements are incorporated in NEM system, the coherent dynamics of Cooper pairs open new routes for controlling vibrations via quantum proximity effects [1].

We investigate a suspended CNT coupled to two normal metal electrodes and superconducting scanning tunneling microscope (STM) tip. We show that depending on parameters such as tunneling strength and the quantum dot (QD) level position, the system exhibits either pumping (regime resulted in appearance of the self-sustained oscillations) or cooling (regime characterized by the suppression of vibrations) of the mechanical subsystem. The mechanism is rooted in the coherent exchange of Cooper pairs between the SC tip and movable QD, providing an electromechanical coupling reminiscent of *covalent bonding* in molecules and distinct from conventional charge- or spin-based mechanisms.

We assume that the CNT suspended between two normal leads biased by voltage V and coupled via a vacuum barrier to an SC STM tip, see Fig. 1. The CNT is modeled as a movable two-fold degenerate single-level QD with fundamental bending mode frequency ω_0. The total Hamiltonian of the system reads

$$H = H_N + H_S + H_{QD} + H_{tun}. \qquad (1)$$

where H_N describes the biased normal leads, H_S is the BCS Hamiltonian of the SC tip, H_{QD} accounts for the electronic level ε_0 and CNT vibrations, H_{tun} describes tunneling between the QD and electrodes. The QD Hamiltonian reads as follows

$$H_{QD} = \sum_\sigma \varepsilon_0 d_\sigma^\dagger d_\sigma - \Delta_d e^{\zeta\hat{x}} \left(d_\uparrow^\dagger d_\downarrow + h.c.\right) + \frac{\hbar\omega_0}{2}(\hat{x}^2 + \hat{p}^2). \qquad (2)$$

with $\hat{x}$, $\hat{p}$ the dimensionless CNT (QD) displacement and momentum operators. The SC proximity effect (second term in Eq. (2)) induces an intra-dot pairing term of strength $\Delta_d \propto |t_S|^2$, while tunneling to normal leads introduces a broadening of the QD energy level, Γ. Crucially, the SC tunneling amplitude depends exponentially on CNT displacement, generating an effective *covalent* electromechanical coupling.

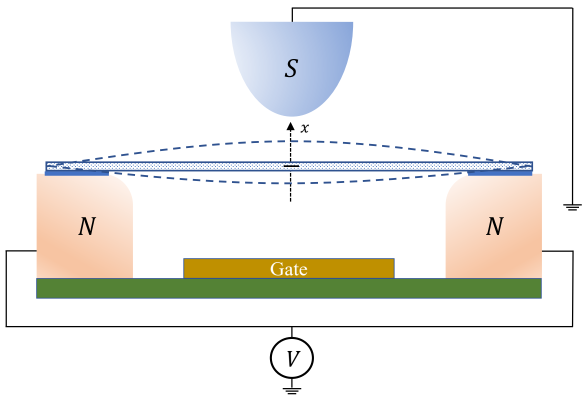

Figure 1: Schematic of the superconducting–normal metal hybrid NEM device. A suspended CNT, which is modeled as QD, is placed between two normal metal leads equally biased with voltage V. A grounded SC lead placed near the CNT-QD induces the proximity effect in the QD and, thus, provides for electromechanical coupling via the CNT's bending-dependent tunnel amplitude.

The electronic and mechanical subsystems are described within the reduced density matrix framework. After tracing out lead degrees of freedom, the dynamics of the CNT–QD system follow a master equation:

$$\dot{\hat{\rho}} = -i[H_{QD}, \hat{\rho}] + i\Delta_d[e^{\zeta\hat{x}}(d_\uparrow^\dagger d_\downarrow^\dagger + h.c.), \hat{\rho}] - \mathcal{L}_e[\hat{\rho}],$$

where $\mathcal{L}_e[\hat{\rho}]$ is a Lindblad superoperator describing incoherent tunneling with the normal leads. To analyze the mechanical subsystem, the density matrix is transformed into a Wigner function, $W_\Sigma(x,p)$. Using perturbation theory in the small parameter ω_0/Γ, the master equation reduces to a Fokker–Planck-like equation for the vibration amplitude A:

$$\left\{\tilde{\gamma}(A)A + \tilde{D}(A)\frac{d}{dA}\right\} W_\Sigma^{(0)}(A) = 0, \qquad (3)$$

where $\tilde{\gamma}(A)$ is an effective damping and $\tilde{D}(A)$ a diffusion coefficient induced by electronic processes. The stationary solution reads as

$$W_\Sigma^{(0)}(A) = \mathcal{Z}^{-1} \exp\left[-\int_0^A dA' A' \frac{\tilde{\gamma}(A')}{\tilde{D}(A')}\right].$$

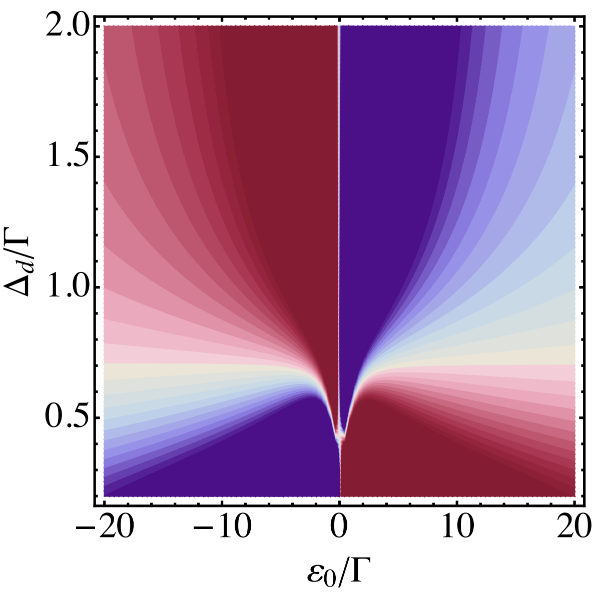

Figure 2: Effective inverse temperature T_{eff}, see Eq. (4), as a function of the CNT-QD's energy level position ε_0 and normalized tunnel coupling with the superconducting STM tip Δ_d/Γ. The blue color scheme indicates the regime of cooling (i.e., a ground state solution with the amplitude of mechanical oscillations $A = 0$ is stable), while the red color scheme indicates the regime of self-sustained oscillations (the solution with $A = 0$ is unstable).

The sign of the effective damping at small amplitude, $\tilde{\gamma}(0)$, distinguishes two qualitatively different regimes. If $\tilde{\gamma}(0) > 0$, the distribution function is peaked at $A = 0$, indicating that the mechanical subsystem is cooled toward its ground state. In this cooling regime one can assign an effective temperature T_{eff}, which in the adiabatic limit is approximately $T_{eff} \approx \Gamma/2$ ($\Delta_d \gg \Gamma$).

Conversely, if $\tilde{\gamma}(0)<0$, the state with $A = 0$ is unstable and the CNT develops finite-amplitude oscillations. These oscillations saturate at an amplitude A_M determined by the condition $\tilde{\gamma}(A_M)=0$. The corresponding Wigner distribution is ring-shaped, signaling stable self-sustained vibrations. This pumping regime is analogous to lasing effect, with the vibrational mode playing the role of a photon cavity field.

The transition between regimes depends on the ratio Γ/Δ_d and the position of the QD level ε_0. At $\varepsilon_0 = 0$, the crossover occurs around $\Gamma/\Delta_d \approx 2.4$, while while for large $|\varepsilon_0|$ the transition moves toward $\Gamma/\Delta_d \approx \sqrt{2}$. Physically, the mechanism arises from the asymmetry of electronic transitions. Injection of single electrons from the normal leads favors the sequence $|0\rangle \to |\sigma\rangle \to |2\rangle$, where $|0\rangle$ and $|2\rangle$ denote empty and doubly occupied QD states. The superconducting proximity effect coherently mixes $|0\rangle$ and $|2\rangle$, and transitions between them can absorb or emit vibrational quanta. For $\varepsilon_0 > 0$, emission dominates (pumping), whereas for $\varepsilon_0 < 0$, absorption prevails (cooling). The competition between coherent Cooper-pair tunneling and incoherent single-electron tunneling produces the stability diagram observed in the analysis, see Fig. 2.

In conclusion, the exchange of Cooper pairs with a SC electrode generates a unique quantum NEM *covalent* coupling in a CNT resonator. This interaction can either suppress vibrations by cooling the mechanical subsystem to an effective temperature T_{eff}, or amplify vibrations into stable self-sustained oscillations with amplitude A_M. The outcome is controlled by the tunnel couplings and the electronic level position, providing a tunable platform where SC proximity effects govern mechanical motion.

[1] A. V. Parafilo, L. Y. Gorelik, H. C. Park, R. I. Shekhter, J. Low Temp. Phys. **210**, 150 (2023).

2.22 Unsupervised Techniques to Detect Quantum Chaos

D. Nemirovsky, R. Shir, D. Rosa, V. Kagalovsky

In this paper [1], we propose the use of *unsupervised techniques* to detect the quantum chaotic properties of a given Hamiltonian under investigation. More in detail, we will use the so-called *Self-Organizing Maps* (SOMs) to detect a chaos/integrability transition in a set of single-particle Hamiltonians, without assuming any prior knowledge of the properties of the Hamiltonians considered: In the process of unsupervised learning, the SOM distinguishes and classifies the quantum Hamiltonians by itself. Our results show that a SOM can detect the onset of a chaotic/integrable transition in a set of single particle Hamiltonians that make a transition from being Poisson-like uncorrelated to RMT-like correlated in terms of a single parameter. As intrinsic in the SOMs framework, the algorithm can detect the transition without the need for any previous knowledge of the Hamiltonian under consideration.

The level repulsion feature is usually studied via the distribution of spectral nearest-neighbor spacings. The three random matrix ensembles, GOE, GUE and GSE, correspond to the three possible distributions of nearest-neighbor spacings for Hermitian Hamiltonians (with real eigenvalues), and make up the three universality classes of Hermitian random matrices.

In this work, the symmetries of the Hamiltonian of the quantum system we will study tell us that the spectral statistics will fall into the universality class of the GUE ensemble – when the Hamiltonian is in its chaotic regime.

In this work, we will consider Hermitian random matrices that can be obtained from adjacency matrices of random graphs, with an extra degree of randomness given by random weights in their entries. The graph structure, $G_{N,k}$, of a graph with N vertices and $N \cdot k$ edges is encoded in an $N \times N$ adjacency matrix with entries $\{A_{ab}\}_{a,b=1}^{N}$ with $|A_{ab}| = 1$ if vertex a is connected with vertex b, and $A_{ab} = 0$ otherwise. Clearly, since we assume that the graph has in total $N \cdot k$ edges, A_{ab} turns out to be quite sparse, with only $2Nk$ non-vanishing entries. We also assume that A_{ab} is a *directed* adjacency matrix, with $A_{ab} = -A_{ba}$. On top of the random graph structure, we add random weights to the edges, such that the entries of the matrix we will be studying are given by

$$H_{ab} = i\, r_{ab} A_{ab} \tag{1}$$

with $r_{ab} = r_{ba}$ are real random numbers taken from a Gaussian distribution with zero mean, and variance $\overline{r_{ab}^2} = \frac{N-1}{2N\,k}$. The imaginary i is put in to make the matrix Hermitian.

To study how chaotic properties of H given in (1) build up as a function of the graph's rewiring probability, p, we will use a spectral indicator constructed from local spectral statistics. For an ordered set of eigenvalues $E_1 \leq E_2 \leq \cdots \leq E_N$, the nearest-neighbor level spacings are given by the set $\{s_i\}_{i=1}^{N-1}$ where $s_i = E_{i+1} - E_i$. As mentioned above, to study nearest-neighbor level spacings statistics and compare them with those of random matrices, the spectrum needs to be unfolded to a flat, unit average density. To avoid the need to perform this unfolding, a different local spectral indicator is used, which effectively eliminates the dependence of the local spectral statistics on the global density of states, namely, the spectral ratios.

The ratios of level spacings are given by the set $\{R_i\}_{i=1}^{N-2}$ where $R_i = s_{i+1}/s_i$. The single-number indicator, often dubbed as "r-ratio" and defined as the average value of $r_i = \min\left(R_i,\, \frac{1}{R_i}\right)$ turns out to be particularly useful as a quick indicator of spectral chaos vs integrability. For matrices taken from the GUE it can be shown that their spectrum satisfies $\langle r \rangle \approx 0.5996$, while for a spectrum with uncorrelated energy levels, where the level spacings follow a Poissonian distribution, $\langle r \rangle \approx 0.38629$.

In Fig. 1 we show the transition from a Poissonian to a GUE value of $\langle r \rangle$ as the rewiring probability p increases from near zero to 1. The figure also shows that by increasing the system size the crossover becomes steeper and steeper, with a fixed point (where all curves meet) located at $p \approx 0.02$.

In summary, the analysis of the r-ratio clearly shows that the set of Hamiltonians defined by Eq. (1) make a transition from being Poissonian (at small p) to being RMT-correlated (at large values of p). By considering the behavior of this crossover while increasing the system size, we are led to conjecture that this crossover turns out to be a genuine transition (*i.e.* a step function in the large N limit) located at $p \approx 0.02$.

Now we show how a self-organizing map can detect the same transition. SOMs are designed to organize high-dimensional input data, such as sequences of random numbers, into clusters with shared characteristics among the neurons comprising the output layer. we will feed the SOM with the Hamiltonian matrix itself, without proceeding with any diagonalization procedure. To perform SOM analysis of the input data, the initial matrix of $N \times N$ size was converted into an input one-dimensional vector of size N^2. We generated 10^5 samples in the $[10^{-4}, 1.0]$ interval of rewiring probabilities, obeying a log-uniform distribution from which a data array was generated for unsupervised learning of a neural network.

After normalizing the number of hits in each of the output neurons, we noticed that only some neurons respond to changes in rewiring probability. The number of hits in these neurons increased sharply as the rewiring probability approached the value of 0.2. Indeed, the serial numbers of these neurons depend on the size of the system and do not obey a particular pattern. However, as the size of the system increases ($N = 56, 84$), the plot of dependence on rewiring probability changes, and three easily identifiable regions are found on it, differing in the slope of the resulting line. In Fig. 2, three sections with different slopes can be clearly distinguished, and the transition points between them correspond to the values of $p = 5 \times 10^{-3}$ and $p = 0.2$ for the rewiring probability. These probability values are in very good agreement with the values presented in Fig. 1 and are consistent with the boundaries of the transition from Poissonian spectral statistics to GUE spectral statistics.

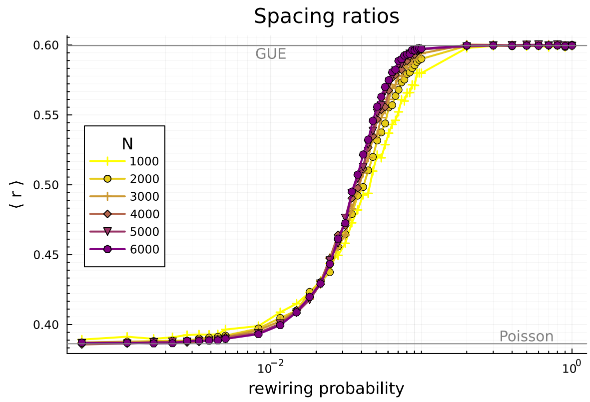

Figure 1: The average value of r_i for a Watts-Strogatz graph with $k = 2$ and different values of N as a function of the rewiring probability p.

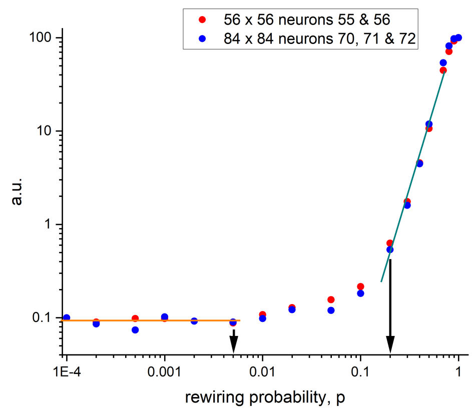

Figure 2: Normalized number of hits in neurons responding to changes in rewiring probability for systems of dimensions 56×56 and 84×84.

[1] D. Nemirovsky, R. Shir, D. Rosa, and V. Kagalovsky, Low Temp. Phys. **50**, 1127 (2024).

Chapter 3

Details and Data

3.1 Visitor (and Workshop) Program

Aiming at combining the scientific research excellence with the exchange of knowledge at the highest level, the PCS offers an active Visitor (and Workshop) Program. As the key element of the structure of the Center, it is deciding for the PCS' unique character of an international research hub. Visiting scientist positions are available at nearly all academic career levels, starting from the Ph.D. students, through the young postdoctoral researchers, to the senior scientists choosing the PCS for their sabbaticals. The duration of visits is fully flexible, we support research stays ranging from brief (a few days), through short- (up to a month), to long-term (several months or years). We offer a lively, comfortable research environment, supporting visitors not only financially, but also logistically, allowing them to focus on their scientific work. Individual guest scientists usually divide their research activities between independent work and collaboration with the PCS members and visitors, also participating actively in our seminar program.

Visitor Program provides comprehensive support not only for guest scientists coming for individual visits (e.g. collaboration meetings, Ph.D. student training, sabbatical stay), but also manages the entire logistics and organization of seminars, colloquia, symposia, and the so-called advanced study groups (ASG). In 2022 – 2025, 210 (onsite: 162 & online: 48) scientists from over 31 countries visited the Center, both on the individually organized visits, and as ASG members.

In addition to hosting a large number of individual short- and long-term visitors and ASG members, the PCS organizes yearly several international workshops held on our premises. In 2022 – 2025, a total of 915 external workshop participants attended our 13 workshops. Each workshop focuses on a different topic of current interest, with a number of internationally recognized specialists invited by the scientific coordinators to present their work, and the organization remaining fully in the hands of the Visitor Program. For future reference, we collect all the workshop presentations (invited, contributed, posters) and post them online. For the PCS members and visitors, workshops provide an excellent opportunity for scientific interactions and forging collaborations – in addition to the day-to-day lively research environment with frequently held seminar talks, ASG discussions, and regular contacts with numerous visitors.

3.1.1 International Workshops

- *Quantum Computing, Complexity and Control*
  International Workshop: July 28 – August 1, 2025
  Scientific coordinators: A. del Campo, B. Bhattacharjee, S. Flach
  47 participants from 12 countries (including 29 participants from Korea)
- *Exciton-Polaritons in Semiconductor Microstructures and Quantum Optics*
  International Workshop: April 28 — May 2, 2025
  Scientific coordinators: A. Natlitov, M. Fraser, S. Koniakhin
  52 participants from 7 countries (including 35 participants from Korea)
- *Computational Approaches to Magnetic Systems*
  International Workshop: February 18 — 20, 2025
  Scientific coordinators: H.-S. Kim, B. Kim, A. Go, S. Kim, C.-J. Kang, C. H. Kim
  76 participants from 9 countries (including 61 participants from Korea)
- *Effective Field Theory Beyond Ordinary Symmetries*
  International Workshop: December 2 – 6, 2024
  Scientific coordinators: D. X. Nguyen, T. Brauner, C. Hoyos, S. Moroz, D. T. Son, M. M. Roberts
  101 participants from 19 countries (including 57 participants from Korea)
- *Flatbands and High-order Van Hove Singularities*
  Intercontinental Binodal Workshop: May 27 — June 7, 2024
  Scientific coordinators: S. Flach, B.-J. Yang, L. Classen, C. Chamon, J. Betouras
  76 participants from 11 countries (including 52 participants from Korea)
  *Intercontinental Binodal Workshop (Daejeon & Dresden)

- *Correlation and Topology in Quantum Matter*
  KIAS-IBS-PCS Workshop: December 18 — 21, 2023
  Scientific coordinators: K. Hwang, M.-J. Park, G. Y. Cho, S. Lee, D. N. Xuan, Y.-B. Kim
  64 participants from 6 countries (including 50 participants from Korea)
- *Polaritons in Emerging Materials*
  International Workshop: September 11 — 15, 2023
  Scientific coordinator: I. Savenko, Y.-H. Cho
  69 participants from 9 countries (including 42 participants from Korea)
- *Computational Approaches to Magnetic Systems*
  IBSPCS-APCTP International Workshop: August 22 — 25, 2023
  Scientific coordinator: B. Kim, A. Go, S. Kim, H.-s. Kim, C.-J. Kang, C. H. Kim
  63 participants from 8 countries (including 51 participants from Korea)
- *Condensed Matter Solitons*
  International Workshop: June 28 — 30, 2023
  Scientific coordinator: S. K. Kim, S. B. Chung, M. J. Park, Y.-i. Shin, J.-H. Kim
  56 participants from 9 countries (including 46 participants from Korea)
- *Complex Condensed Matter Systems*
  Asian Network School and Workshop: November 6 — 10, 2023
  Scientific coordinators: S. Flach, P. Pearce, T. M. Tien, T. X. Hoang, N. H. Quang, N. H. Viet
  106 participants from 7 countries (including 22 participants from Korea)
- *Topological Quantum Matter*
  Focus Workshop: December 12, 2022
  Scientific coordinator: Y. B. Kim, M. J. Park, S. Park, K. H., S. Lee, B.-J. Yang
  30 participants from 2 countries (including 28 participants from Korea)
- *Computational Approaches to Magnetic Systems*
  IBSPCS-APCTP International Workshop: August 17 -– 19, 2022
  Scientific coordinator: C. H. Kim, C.-J. Kang, S. Kim, H.-S. Kim, I. Di Marco, A. Go, B. Kim
  63 participants from 8 countries (including 73 participants from Korea)
- *Condensed Matter Solitons*
  International Workshop: June 29 — July 1, 2022
  Scientific coordinators: S. K. Kim, S. B. Jung, M. J. Park, Y.-i. Shin
  112 participants from 15 countries (including 83 participants from Korea)

Future overview

- *Novel Perspectives in Non-Hermitian Physics: From Condensed Matter to Optical and Beyond*
  International Workshop: October 29 – 31, 2025
  Scientific coordinators: Z. Yang, K.-M. Kim, J.-W. Ryu, C.-H. Yi
- *Complex Condensed Matter Systems*
  Asian Network School and Workshop: Nov. 10 – 14, 2025
  Scientific coordinators: C. Villagonzalo, P. Pearce, S. Flach, K.-S. Kim

3.1.2 Advanced Study Groups

- *Coherent Charges, Spins and Phonons in Superconducting Weak Links*
  Advanced Study Group: Sep. 01 – Nov. 01, 2025
  Convener: R. Shekhter (University of Gothenburg, Sweden)
  Members: S.-J. Choi, L. Gorelik, J.-H. Han, C. Kim, N. Myoung, A. Parafilo, D. Radić, J. Suh, C.-H. Yi, D. Chowdhury
- *Spin-orbit coupling in transition metal complexes: from model to realistic system*
  Advanced Study Group: : Jul. 14 – Jul. 18, 2025
  Convener: B. Kim (Kyungpook National University, Korea)
  Members: H. Kim, C.-J. Kang, A. Go, S. Kim, H. C. Park, S. Y. Park, M. Kim, J. Han, K. Kim, C. H. Kim, H. J. Lee, B. H. Kim, K. M. Kim
- *Theoretical Challenges of Quantum Magnets with Complex Anisotropies*
  Advanced Study Group: May 11 – Jun. 07, 2025
  Convener: B. Tomasello (University of Catania, Italy), T. Ziman (Institut Laue-Langevin, Grenoble, France)
  Members : M. Mori, K. Yamamoto, T. Ohtsuki, K. M. Slevin, K.-M. Kim, M. J. Park, A. Andreanov, O. Utesov, S. K. Kim
- *Low-dimensional magnetism and quantum phenomena from computational perspectives*
  Advanced Study Group: Aug. 19 – Aug. 23, 2024 and Feb. 17 – Feb. 21, 2025
  Convener: H. Kim (Kangwon National University, Korea)
  Members: C.-J. Kang, A. Go, S. Kim, B. Kim, H. C. Park, S. Y. Park, M. Kim, J. Han, K. Kim, C. H. Kim, H. J. Lee, B. H. Kim, K. M. Kim
- *Coherent Charges, Spins and Phonons in Superconducting Weak Links*
  Advanced Study Group: Apr. 02 – Jun. 02, and Sep. 03 – Nov. 03, 2024
  Convener: R. Shekhter (University of Gothenburg, Sweden)
  Co-Convener: H. C. Park (Pukyong National University, Korea), S. Park (PCS IBS)
  Members: A. Aharony, S.-J. Choi, O. Entin-Wohlman, L. Gorelik, J.-H. Han, M. Jonson, C. Kim, N. Myoung, A. Parafilo, D. Radić, J. Suh, C.-H. Yi, D. Chowdhury
- *Entanglement and Dynamics in Quantum Matter*
  Advanced Study Group: Jun. 19 – Jun. 23, 2023
  Convener: Y. B. Kim (University of Toronto, Canada)
  Members: E.-G. Moon, S. Lee, G. Y. Cho, M. J. Park, D. X. Nguyen, B. H. Kim, K.-M. Kim, J. Han, S. Verma
- *Computational study on strongly correlated low-dimensional magnetic systems*
  Advanced Study Group: Jul. 18 – 22, Dec. 19 – 21, 2023 and Jan. 29 – Feb. 2, 2024
  Convener: C.-J. Kang (Chungnam National University, Korea)
  Members: A. Go, S. Kim, B. Kim, H. C. Park, H. Kim, S. Y. Park, M. Kim, J. Han, K. Kim, C. H. Kim, H. J. Lee
- *Tensor Network Approaches to Many-Body Systems*
  Advanced Study Group: Jul. 10 – Jul. 21, 2023 and Jan. 1 – Feb. 28, 2024
  Convener: H.-Y. Lee (Korea University Sejong, Korea)
  Members: H. C. Park, N. Kawashima, Y.-J. Kao, S. Todo, K. Harada, T. Suzuki, S. Morita, T. Okubo, R. Kaneko, C.-M. Chung, D.-H. Kim, H. J. Lee, H.-H. Tu, J.-W. Li, S. Lin, W.-L. Tu, Y.-T. Oh

- *Unusual order in incommensurately stacked multilayers*
  Advanced Study Group: May 15 – Aug. 30 and Nov. 22, 2023 – Jan. 21, 2024
  Convener: P. Moon (New York University in Shanghai, China)
  Members: M. J. Park, Y. Kim, J.-W. Rhim, N. Myoung, H. C. Park, J.-R. Ahn, H. Yang, Y. W. Son, S. Kim
- *Quantum-Functional Mesoscopic Weak Links*
  Advanced Study Group: Apr. 02 – Jun. 02, Aug. 6 – Aug. 20, and Sep. 02 - Nov. 02, 2023
  Convener: R. Shekhter (University of Gothenburg, Sweden)
  Co-Convener: H. C. Park (Pukyong National University, Korea)
  Members: A. Aharony, S.-J. Choi, O. Entin-Wohlman, L. Gorelik, J.-H. Han, M. Jonson, C. Kim, N. Myoung, A. Parafilo, S. Park, D. Radić, J. Suh, C.-H. Yi
- *Entanglement and Dynamics in Quantum Matter*
  Advanced Study Group: Sep. 1, 2022 – Sep. 1, 2024
  Convener: Y. B. Kim (University of Toronto, Canada)
  Members: E.-G. Moon, S. Lee, G. Y. Cho, M. J. Park, D. X. Nguyen, K.-M. Kim, J. Han, S. Verma
- *Computational methods in transition metal compounds: correlations and magnetism*
  Advanced Study Group: Jun. 20 – 24, 2022 and Feb. 13 – 17, 2023
  Convener: A. Go (Chonnam National University, Korea)
  Members: S. Kim, B. Kim, H. C. Park, H. Kim, S. Y. Park, M. Kim, C. J. Kang, J. Han, K. Kim, C. H. Kim, H. J. Lee
- *Hidden order in incommensurately stacked multilayers*
  Advanced Study Group:
  Convener: P. Moon (New York University in Shanghai, China)
  Members: M. J. Park, Y. Kim, J.-W. Rhim, N. Myoung, H. C. Park, J.-R. Ahn, H. Yang, Y. W. Son
- *Deep Learning in Quantum Phase Transitions*
  Advanced Study Group: Jun. 13 – Jul. 8, 2022
  Convener: V. Kagalovsky (Shamoon College of Engineering, Israel)
  Members: S. Kravchenko, M. Fistul, T. Ohtsuki, K. Slevin, I. Yurkevich, A. Andreanov
- *Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links*
  Advanced Study Group: Jan. 29 – Feb. 27 and Jul. 25 – Sep. 24, 2022
  Convener: R. Shekhter (University of Gothenburg, Sweden)
  Co-Convener: J. Suh (KRISS, Korea)
  Members: A. Aharony, O. Entin-Wohlman, L. Gorelik, M. Jonson, C. Kim, H. C. Park, D. Radić, J. Suh

3.1.3 Workshop Reports

Quantum Computing, Complexity and Control
Scientific Coordinators: Budhaditya Bhattacharjee, Adolfo del Campo, and Sergej Flach

The international workshop on Quantum Computing, Complexity and Control brought together researchers working on the interplay between quantum information science, quantum chaos, optimal control, and complexity theory. Held at the Center for Theoretical Physics of Complex Systems (PCS), IBS in Daejeon, Korea, the five-day event featured a stimulating mix of talks, poster sessions, and informal discussions. The program comprised 24 talks — 17 invited and 7 contributed — and included two dedicated poster sessions, an IBS colloquium, and a mid-week excursion and banquet. Notably, the colloquium talk by Prof. Marin Bukov explored the utility of periodically driven systems for quantum simulation, reflecting one of the central themes of the workshop. Participants came from a wide geographic distribution, including Korea, Japan, India, China, Luxembourg, Germany, Spain, Russia, and the United States. The workshop hosted a total of about 37 participants, with strong involvement from young researchers and students, including 8 PCS members and associates. Some key highlights and open questions discussed during the workshop included:

- Role of Krylov complexity as a diagnostic of quantum chaos and its dependence on operator choice and initial states.
- Control protocols such as counterdiabatic driving and their robustness in open or critical systems.
- The application of machine learning techniques to identify ergodicity breaking and dynamical phase transitions.
- Non-Hermitian random matrix models, with implications for the classification of open quantum systems.

The extended lunch breaks and the mid-week excursion fostered informal exchanges and collaborative discussion, particularly useful for early-career researchers. The welcome and colloquium dinners were also well appreciated by attendees and provided opportunities for cross-disciplinary interaction. The workshop included 2-hour discussion sessions each day where participants discussed potential collaborative projects, open problems in quantum complexity and control, and possibilities for a follow-up meeting in the near future.

Conclusion

The workshop successfully met its goals of fostering dialogue across multiple subfields of quantum science and promoting new research collaborations. Feedback from participants was overwhelmingly positive, particularly regarding the scientific quality of the program and the hospitality of the PCS Visitors Program. The organizers express gratitude to all participants and the IBS staff for their contributions to making this event a success.

Exciton-Polaritons in Semiconductor Microstructures and Quantum Optics
Scientific Coordinators: Sergei Koniakhin, Anton Nalitov, and Michael Fraser

The main aims of the workshop were to discuss recent progress in physics of exciton-polaritons in semiconductor microstructures and quantum optics and to enable researchers from diverse backgrounds to interact and forge new collaborations.

Major topics of the workshop included recent theoretical and experimental studies of nonequilibrium bosonic condensation and superfluidity of exciton-polaritons, emergent non-Hermitian, topological, and nonlinear photonic phenomena, novel implementations of optical microstructures including planar photonic crystals and microwires, as well as quantum polaritonics and optics with the stress on squeezed light application for quantum computations. In addition, the program featured several invited talks from experts in related fields, covering topics ranging from atomic Bose-Einstein condensates to photonic crystals and topological photonics. Among highlights of the workshop were the opening plenary talk by Prof. Pavlos Savvidis and the colloquium talk by Prof. Alberto Bramati on quantum fluids of light.

The workshop benefited from a diverse cast of 34 invited speakers and participants representing 8 countries, including 4 from PCS. The majority of external participants were from Korea (about 20), followed by Russian Federation (8). The remainder came from further afield (Europe, USA, and Japan). The informal discussions in the amiable atmosphere held during the workshop are anticipated to lead to stronger collaborations both within the region and worldwide. There was an excellent balance between experimental (15) and theoretical (13) talks.

Many participants appreciated the unique seminar-style format promoting questions and active discussion during the talks, as well as surplus coffee break providing a good opportunity for informal interactions. During this time several key open problems for the field were identified and debated:

- The new generation of optical micro- and nanostructures supporting polariton condensation require a proper microscopic approach to description of strong light-matter coupling and establishment of coherence in the equilibrium and nonequilibrium regimes.
- The quantum aspects of the exciton-polariton physics remains largely unrevealed and, despite extensive experimental research, most phenomena involving polariton condensation are described with semiclassical models based on the mean-field approximation.
- Polaritonics presents huge interest for adjacent fundamental and applied fields as a platform combining optical tunability and accessibility on one hand with many characteristics of condensed matter systems: new interdisciplinary advances are expected.

It is clear that the interplay of polaritonics and quantum optics is likely to be the new horizon in the following years, and closer integration of the two fields will follow.

To conclude, the main goals of the workshop were achieved and feedback among the participants was highly positive, particularly regarding the organizational support provided by the Visitors Program.

Computational Approaches to Magnetic Systems (CAMS-2025)
Scientific Coordinators: Bongjae Kim, Ara Go, Chang-Jong Kang, Choong Hyun Kim, Heung-Sik Kim, and Sooran Kim

Magnetism remains a central topic in condensed matter physics, with fundamental questions that challenge both theoretical and computational approaches. The complex interplay between localized and itinerant electronic states, spin-orbit interactions, and electron correlations necessitates continuous advancements in numerical techniques and theoretical frameworks. While mean-field approximations provide useful insights, a deeper understanding of magnetism—particularly in low-dimensional and strongly correlated systems—requires the application of many-body and phenomenological approaches. Computational magnetism remains an ever-evolving field, driving new discoveries through the development of advanced methodologies.

Building upon the success of previous workshops in 2018, 2019, 2022, and 2023, the

2025 Workshop on Computational Approaches to Magnetic Systems (CAMS 2025) provided a platform for discussing recent theoretical and computational advances. The workshop covered a broad spectrum of topics, including the development of novel computational methods, the exploration of exotic magnetic states, machine-learning-assisted approaches, and emergent quantum phenomena in magnetic materials.

The workshop featured 18 invited speakers, including two online talks, representing institutions from Korea, Sweden, Germany, Poland, UK, China, and Japan. A poster session allowed students and early-career researchers to actively engage with experts in the field. Over 70 participants took part in the discussions, which extended beyond the formal sessions into informal gatherings during coffee breaks and meals.

Key Topics Discussed at CAMS 2025

1. Advancements in spin Hamiltonians and correlated electronic structure calculations (MJ Han, S Ryee, CH Kim, H Yoon, N Iwahara)

2. Studies on exotic magnetism and magnetic materials (M Park, B Sanyal, C Etz, W Sun, D Nafday, T Oh)

3. Large-scale atomistic magnetic dynamics and magnetotransport (A Delin, K-W Kim, A Edstrom)

4. Charge- and spin-density wave phenomena in low-dimensional magnetic systems (I Di Marco, S-W Kim, C Park)

5. Machine-learning approaches in studying magnetic systems (S Kim, H Yoon)

From a scientific perspective, the workshop was a resounding success. The interactive format encouraged lively discussions, and several new collaborations have already been initiated. While workshops with a strong emphasis on discussion are common in the USA and Europe, they remain relatively rare in Korea. The CAMS workshop continues to serve as a model for fostering young researchers and facilitating meaningful scientific exchanges in computational magnetism.

We look forward to making this an annual event and anticipate that the insights gained from this workshop will drive further advancements in the field.

Effective Field Theory Beyond Ordinary Symmetries
Scientific Coordinators: Tomáš Brauner, Carlos Hoyos, Sergej Moroz, Dung Xuan Nguyen, Matthew M. Roberts, and Dam Thanh Son

The workshop on Effective Field Theory Beyond Ordinary Symmetries brought together 26 distinguished speakers and participants from 23 countries to discuss groundbreaking developments in effective field theory (EFT). Topics spanned higher-form symmetries, multipole symmetries and fractons, noninvertible symmetries, topological quantum phases, advanced applications in quantum many-body systems, and quantum gravity and cosmology.

Workshop Goals

The event aimed to stimulate the exploration of novel applications of generalized symmetries in theoretical physics. By bridging formal theory and practical applications, the workshop provided a fertile ground for identifying open problems and fostering collaboration across diverse research domains.

Scope of Talks

This workshop's program brought together theoretical physicists to examine cutting-edge directions in effective field theory, focusing on frameworks that extended traditional notions of symmetry. The talks presented new mathematical tools and physical insights that emerged from these broadened symmetry concepts, including their roles in characterizing topological phases of matter, understanding novel dualities, and formulating refined low-energy effective descriptions of strongly coupled quantum systems. By exploring how these emerging structures interplayed with anomalies, defects, and topological quantum field theories, the workshop aimed to push beyond ordinary symmetry-based paradigms and paved the way for a deeper understanding of quantum field phenomena across both high-energy physics and condensed matter contexts.

Outcomes and Feedback

The workshop succeeded in encouraging dialogue between researchers from different areas of theoretical physics. The inclusive format, which balanced accessibility and depth, was particularly appreciated by participants. Suggestions for improvement included adjusting the schedule to allow more time for discussions.

Conclusion

The workshop fulfilled its objectives of advancing knowledge about generalized symmetries and identifying promising directions for future research. Participants expressed strong interest in organizing follow-up meetings to continue the exchange of ideas and strengthen international collaboration.

Flat Bands and High-order Van Hove Singularities
Scientific Coordinators: Bohm Jung Yang and Sergej Flach

The main aims of the workshop were to discuss recent progress in the study of quantum many-body states of matter achieved by various band engineering methods such as by globally reducing the bandwidth, by locally inducing higher-order van Hove points, or by designing lattice geometries which yield flat bands. The workshop was held in a novel format, with participants from two nodes, one in Europe (Dresden, Germany) and one in Asia (Daejeon, Korea) by running a part of the program in hybrid modes such that the talks could be attended from both nodes at the same time.

Major topics of the workshop included recent theoretical and experimental studies of van Hove-like singularities, Lifshitz transition, flat bands, symmetry and topology, quantum geometry, fractional topological insulators, strongly correlated materials, moiré materials, graphene, electronic instabilities, and many-body physics.

The workshop benefited from a diverse cast of 52 invited speakers (16 from Daejeon, 36 from Dresden) and participants representing 18 countries, including 16 from PCS. The majority of external participants were from Korea (about 52) followed by China and Japan. The remainder came from further afield (Europe and Singapore). The informal discussions held during the workshop are anticipated to lead to stronger collaborations within the region. There was an excellent balance between experimental and theoretical talks and good participation in the poster session (16 contributed posters).

After the workshop, there were constructive reviews to improve future events. During the first week of the hybrid sessions, there was an avoidable imbalance in the number of invited talks and their distribution over both nodes. This was due to an existing workshop proposal from the Dresden site and the limited time to come up with a set of invited speakers from the Daejeon node. For the next binodal workshop, the scientific coordinators on both sides could make a joint balanced proposal at the initial stage. The time difference between two nodes should be more carefully considered in the program to avoid a reduction in the number of participants. Also, a longer duration for each talk would be more beneficial to encourage discussion and feedback from both nodes during the sessions.

To conclude, the main goals of the workshop were achieved, and feedback among the participants was highly positive, particularly regarding the novel format of the workshop connecting two continents. There is strong interest in holding another meeting on this topic in the future.

Polaritons in Emerging Materials
Scientific Coordinators: Yong-Hoon Cho, Timothy Liew, and Ivan Savenko

The International Workshop on "Polaritons in Emerging Materials" took place at the Center for Theoretical Physics of Complex Systems (PCS), Institute of Basic Science (IBS), in Daejeon, Republic of Korea, from 11th to 15th of September 2023. This workshop was coordinated by Prof. Yong-Hoon Cho (KAIST, Korea), Prof. Timothy Liew (NTU, Singapore), and Prof. Ivan Savenko (GTIIT, China). During these five days, there have been 21 invited talks, including a colloquium talk, on different aspects of exciton-polariton transport and Bose-Einstein quasi-condensation in semiconductor microcavities in emerging organic and inorganic materials, including spatially patterned periodic structures. A poster session also allowed younger researchers to present their work.

The workshop demonstrated the growing interest of the exciton-polariton research community in:

(i) Experiments on polariton condensation in 0D, 1D, and 2D systems as it follows from enthusiastic talks of Alberto Amo (CNRS, France), Sebastian Klembt (University of Würzburg, Germany), Michael Fraser (RIKEN, Japan), among others. These experiments demonstrated the formation of polariton condensates in structures based on various materials under development.

(ii) Topologically protected states of light have been addressed in the talks of Sven Höfling (Wuerzburg University, Germany), Daniel Leykam (NUS, Singapore), Alexander Cerjan (Sandia National Laboratories, USA), and Suk Bum Chung (University of Seoul). Concepts of non-Hermitian topology and higher-order topology were also introduced within the polaritonic concept by Xingran Xu (Jiangnan University).

(iii) Exciton-Polaritons in novel materials and exotic heterostructures, including a presentation on phase-changing perovskites by Chang-Hee Cho (DGIST, Korea) and two presentations on layered semiconductors by Deep Jariwala (University of Pennsylvania) and Su-Hyun Gong (Korea University).

(iv) Relations to the field of quantum information, including presentations on qubit entanglement by Andrey Moskalenko (KAIST, Korea) and quantum-enhanced measurements Hyang-Tag Lim (KIST, Korea).

(v) Other fundamental aspects of exciton-polaritons, including Rabi oscillations in space and time by Fabrice Laussy (University of Wolverhampton, UK), as well as related topics such as surface plasmons by Myung-Ki Kim (Korea University, Korea).

(vi) Finally, there was a series of talks devoted to the behavior of polaritons in rotating geometries, including the formation of vortices and solitons by Sergei Koniakhin (IBS, Korea), spinning polariton condensates by Alexey Yulin (ITMO, Russia), and stirred polariton condensates by Helgi Sigurdsson (University of Iceland, Iceland).

The overall impression from the Workshop is that unique features of novel materials bring in new physics, while, as exciton-polaritons are ultimately quantum particles, they have potential applications in quantum information. It was also pleasant to see the strong participation of local researchers where the workshop offered a platform for the presentation of local advancements to the international community. The workshop program carefully allowed generous time for discussions and has set the seed for many collaborations in the near future.

Computational Approaches to Magnetic Systems (CAMS-2023)
Scientific Coordinators: Bongjae Kim, Ara Go, Chang-Jong Kang, Choong Hyun Kim, Heung-Sik Kim, and Sooran Kim

There is increasing interest in the fundamentals and application of magnetism. However, the theoretical description of magnetism, either static or dynamic, is not a trivial problem and has been a fundamental topic since the establishment of quantum mechanics in the early 1900s. In fact, despite the long history, various topics on magnetism remained the most challenging tasks in the condensed matter physics community. The physics of magnetism requires the accurate evaluation of competing energies and is manifested in the regime where local and itinerant electron physics meet. For a better understanding of magnetism and related phenomena, diverse theoretical and computational approaches, based on the mean field theory as well as on many-body physics, are required. Also, the phenomenological approaches are also essential for the macroscopic picture. The computational magnetism is an extremely dynamic field, where extensive developments are continuously tried.

In this workshop, continuing with our previous successful practices in 2018, 2019, and 2022, we aim to gather young and active researchers in the field of magnetism and to discuss recent developments. The covered topics include various methodological approaches, static and dynamic aspects, machine-learning related issues, specific examples, and applications.

15 invited speakers (including three online talks), most of them in their early-career stages, from Canada, Taiwan, USA, Israel, Austria, Germany, and Korea, gave cutting-edge talks. More than 50 participants were actively involved in the intense discussion, which had been continued during the coffee breaks. The poster session by younger students offered even more chances for the students to be involved. The list of talks is detailed on the websites.

From the scientific point of view, we believe the workshop has been a great success. The entire participant enjoyed the active questions, comments, and discussions. Some scientific collaborations have already been initiated. The concept of a young and discussion-oriented workshop is often practiced in USA and Europe but is not so common in Korea. Here, we think we are continuously setting nice examples. And we hope we can make this an annual event. We are happy to finish this workshop perfectly. All participants gained some insight and motivation in this field from this workshop.

Condensed Matter Solitons 2023
Scientific Coordinators: Se Kwon Kim, Sukbum Chung, Moon Jip Park, Yong-il Shin, and Jee-Hoon Kim

Overview: This scientific report provides a comprehensive overview of the workshop on "Exploring Topological Solitons in Quantum Materials," which aimed to bring together theoretical and experimental experts to discuss advancements in the understanding of topological solitons in various quantum materials. The workshop focused on topics such as topological superfluids, Majorana fermions and topological materials, skyrmions and spintronics, and non-equilibrium quantum phases.

Participations: The workshop saw the participation of a diverse group of experts, including theoretical and experimental researchers from around the world (9 international speakers and 5 domestic speakers). Each talk consisted of 45 minutes. In addition, there were small poster sessions for the students. The scientific coordinators and organizers ensured representation from various backgrounds, fostering collaborative discussions and interdisciplinary exchanges. The event attracted participants specializing in quantum materials, including magnets, superfluids, superconductors, and multiferroics.

Key Discussions and Future Directions: During the workshop, participants engaged in insightful discussions on the topics of topological solitons in quantum materials. The discussions highlighted advancements in understanding topological solitons such as skyrmions from many different physical setups including magnetism, BEC, and ultracold atomic gases. Participants identified future research directions, including exploring novel materials, investigating soliton–soliton interactions from many different physical contexts, and understanding soliton-induced phase transitions.

Conclusion: The workshop successfully brought together theoretical and experimental experts to discuss advancements and explore the universal physics of topological solitons. The event provided a platform for sharing cutting-edge research developments and fostering collaborations among participants. The scientific coordinators, organizers, and attendees expressed their satisfaction with the workshop's organization and outcomes, indicating a strong interest in future meetings to further explore the exciting field of topological solitons in quantum materials.

Advances in The Physics of Topological and Correlated Matter
Scientific Coordinators: Yunkyu Bang, Sergej Flach, Tae Won Noh, Han Woong Yeom

The IBS-APCTP Conference on Advances in The Physics of Topological and Correlated Matter took place at the IBS Science Culture Center, Daejeon on September 19–23, 2022. It was organized by IBS PCS and funded by the IBS, APCTP, and IBS PCS.

Chairs: Yunkyu Bang (APCTP), Sergej Flach (IBS PCS), Tae Won Noh (IBS CCES), Han Woong Yeom (IBS CALDES)

Local Organizers: Ki-Seok Kim (APCTP), Moon Jip Park (IBS PCS), Jung-Wan Ryu (IBS PCS), Bohm-Jung Yang (IBS CCES)

Overview: Topology plays a pivotal role at the forefront in understanding correlated quantum matter. A plethora of relevant fields, e.g. topological superconductivity and magnetism, fractional Hall effect and spin liquids, non-equilibrium and open quantum systems, turn into exciting platforms to test our insights and to find new exotic states of matter. The main goal of this IBS-APCTP conference is to bring together experts from the above fields to get an overview of the current state and the most recent advances in understanding topological and correlated quantum matter.

Topics include: Fractional excitations and correlated phases, Topological magnets, Non-Hermitian systems, Topological Floquet systems, Non-equilibrium dynamics, Moire materials and topological flat bands, Topological band theory, Machine learning and topology.

Participations: There have been 118 participants (68 in-person / 50 online), 32 invited talks (14 in-person / 18 online), and 16 posters during the workshop on the topics of

- Unusually Large Anomalous Hall Conductivity in CoS_2 and Its Origin (Changyoung Kim)
- Bulk-Boundary Correspondence in Point-Gap Topological Phases (Masatoshi Sato)
- Floquet Engineering and Topological Nonlinear Optics (Takashi Oka)
- Steady Floquet–Andreev States in Graphene Josephson Junctions (Gil-Ho Lee)
- Local Thermodynamic Measurements of Topological States in Magic Angle Graphene (Andrew Pierce)

- Geometry and Multi-Gap States (Robert-Jan Slager)
- Induced Superconductivity in the Fractional Quantum Hall Edge in Graphene Heterostructures (Philip Kim)
- Electronic Topology and Correlations in Kagome Metals (Riccardo Comin)
- Quotient Symmetry Protected Topological Phenomena and Quantum Criticality (Frank Pollmann)
- A Topological Principle for Photovoltaics (Aris Alexandradinata)
- Large Magnetotransport Responses of Topological Van Der Waals Magnets (Jun Sung Kim)
- Spin-Resolved Topology, Partial Axion Angles, and Half Quantum Spin Hall Surface States in Higher-Order Topological Crystalline Insulators (Benjamin Wieder)
- Quantum Geometry and Fractional Chern Insulators in Moiré Materials (Emil J. Bergholtz)
- Zero-Field Superconducting Diode Effect in Twisted Trilayer Graphene (Mathias S. Scheurer)
- Topological Material Search via Symmetry Indicator and Filling Anomaly (Haruki Watanabe)
- Electrical Switching of Magnetic Order in Intrinsic Chern Insulators (Andrea Young)
- Topological Non-Hermitian Origin of Surface Maxwell Waves (Franco Nori)
- Persistent Homology Analysis of Phase Transitions (Daniel Leykam)
- Natural Superlattice Design of Quantum Materials (Joseph George Checkelsky)
- Nonlinear Bosonization of Fermi Surfaces: The Method of Coadjoint Orbits (Dam T. Son)
- Twisted Bilayer Magnets CrI_3 (Moon Jip Park)
- Topological Phases of Discrete Unitary Dynamics (Jeongwan Haah)
- Metrology of Band Topology via Resonant Inelastic X-ray Scattering (Gil Young Cho)
- Non-Reciprocal Frustration: Time Crystalline Order-by-Disorder Phenomenon and a Spin-Glass-like State (Ryo Hanai)
- Fractonic Spin Liquids in Frustrated Magnets (Yong Baek Kim)
- Chirality-Driven Electronic Topology in DNA-Type Chiral Materials (Binghai Yan)
- Machine Learning Quantum Emergence (Eun-Ah Kim)
- Ultrafast Charge Order Dynamics in a Kagome Metal (Nuh Gedik)
- Recent Progress in Non-Hermitian Physics beyond One Dimension (Zhong Wang)
- The Topological Origin of the Non-Hermitian Skin Effect (Chen Fang)
- Emergence of Local Pairing and Global Phase Coherence in Underdoped Cuprates (Yayu Wang)
- Dynamical Fractal and Anomalous Noise in Clean Magnetic Crystal (Roderich Moessner)

Results & Future Perspectives: Topology plays a pivotal role at the forefront in understanding correlated quantum matter. A plethora of relevant fields, e.g., topological magnets, non-Hermitian systems, topological Floquet systems, non-equilibrium dynamics, moiré materials and topological flat bands, topological band theory, and machine learning and topology, turn into exciting platforms to test our insights and to find new exotic states of matter. The main goal of this IBS-APCTP conference was to bring together experts from the above fields to get an overview of the current state and the most recent advances in understanding topological and correlated quantum matter.

We met the main goals of the workshop by having intensive discussions during the workshop. The workshop highlighted recent advances in the fields of topological and correlated matter with 32 brilliant talks (14 in-person / 18 online) and 16 posters. More than 110 participants took part in this workshop in-person or online. We expect that the continuity of this workshop will bring improvement and incremental growth in this research field by providing more opportunities for researchers to meet, interact and exchange innovative ideas in the future, especially, beyond COVID-19.

Computational Approaches to Magnetic Systems (CAMS-2022)
Scientific Coordinators: Ara Go, Chang-Jong Kang, Bongjae Kim, Choong Hyun Kim, Heung-Sik Kim, Sooran Kim, Igor Di Marco

This workshop aims to gather outstanding and active young researchers in the computational and/or theoretical field worldwide and discuss cutting-edge research and current problems in the field of magnetism. The covered topics include various methods, e.g. density functional theory, dynamical mean-field theory, diagrammatic approaches, and field theories. Diverse physical system and phenomena are discussed which includes magnetic/electronic phase transitions, exotic magnetism, topological behaviors, and superconductivity.

The description of a magnetic system is not an easy task to do, because of the complex origin of magnetism where the correct description of both itinerant interaction and localized interaction of electrons is needed. Further, a better description of the magnetism is often key to other material properties such as topology and superconductivity. Computational/numerical approaches are now considered the most important theoretical tool in the study of magnetism. New techniques and algorithms are proposed and shed new light on our understanding of the magnetic systems, where interplay among various degrees of freedom enriches physics. Notable progress can be found not only in the first-principles methodology but also in their cross-border fields. Each method has its strengths and weaknesses depending on the material-specific characteristics.

Our workshop on magnetism is to be a platform for discussions of various aspects of magnetism. Continuing with our previous successful workshops in 2018 (APCTP, Pohang) and 2019 (PCS-IBS, Daejeon), which were at a halt during the COVID-19 period, we are happy to have a fruitful event this time again. This workshop has been planned to bring together the experts in each area, thereby providing a platform to discuss frontier issues. Special attention is paid to providing a network for young researchers with different technical backgrounds and promoting further collaborations. Enabling enough time for the discussion after each talk (total 45 mins), plenty of discussions were there and were continued during the coffee breaks and afterward.

From a number point of view, there were more than 65 registered participants including 7 scientific coordinators and 20 speakers. The invited speakers, most of them in their early-career, are from Japan, India, Romania, Switzerland, China, USA, Singapore, and Korea. The list of talks is detailed on the websites.

From the scientific point of view, we believe the workshop has been a great success. The overall atmosphere was hot by intensive discussions during every talk, and often the discussions continued during coffee breaks and lunchtime. During every break time, the participants actively gathered in mini-groups and discussed livelily. Prolonged discussions were made among some participants after the workshop, and collaborations among the participants are already initiated. The concept of a young and discussion-oriented workshop is often practiced in USA and Europe but is not so common in Korea. Here, we think we are continuously setting nice examples. And we hope we can make this an annual event. We are happy to finish this workshop perfectly. We believe that all participants gained some insight and motivation in this field from this workshop.

Condensed Matter Solitons 2022
Scientific Coordinators: Se Kwon Kim, Sukbum Chung, Moon Jip Park, Yong-il Shin, and Jee-Hoon Kim

Overview: The main goal of the workshop was to bring together international experts on condensed matter physics and discuss the recent advances in the topical subjects on solitons in various condensed matter systems. Such topics related to the skyrmions included skyrmions in magnets, vortices in superconductors, cold atoms, and non-Hermitian topological phases. The workshop got the attention of many international researchers in condensed matter physics, and it brought opportunities to strengthen the networking between domestic researchers and international experts. Among 24 workshop presentations, the colloquium was delivered by Prof. Jim Sauls (Northwestern University), who spoke about "the edge states, solitons & novel phases of topological superfluids."

Participations: Due to the remaining COVID pandemic, the workshop was restricted to an online mode with 24 invited speakers (USA: 7, S. Korea: 7, Germany: 3, China: 3, Sweden: 1, France: 1, Canada: 1, Japan: 1). We received overwhelming responses with 76 participants (S. Korea: 49, Europe: 10, North America: 10, other Asian countries: 7). All our invited talks are currently available on the PCS YouTube channel.

Results & Future Perspectives: We met the main goals of the workshop by having intensive discussions during the workshop. The workshop highlighted recent progress in the fields of solitons in condensed matter systems. Although the workshop was conducted online, the participants actively joined the discussion on various topics across their expertise. We believe that such intensive discussion across various fields will stimulate new ideas and collaborative research projects between various groups. In the future, we expect that the extensions of this workshop can be conducted in the offline environment, and it would further broaden research efforts beyond individual material systems with the goal of learning the universal physics of topological solitons.

3.1.4 External Cofunding of Workshops and Seminars

- *Computational Approaches to Magnetic Systems*
  International Workshop: February 18 – 20, 2025
  – 54% of the workshop budget contributed by the APCTP (Asia Pacific Center for Theoretical Physics, Korea)
- *Effective Field Theory Beyond Ordinary Symmetries*
  International Workshop: December 2 – 6, 2024
  – 6% of the workshop budget contributed by the APCTP (Asia Pacific Center for Theoretical Physics, Korea)
- *Polaritons in Emerging Materials*
  International Workshop: September 11 – 15, 2023
  – 13% of the workshop budget contributed by the APCTP (Asia Pacific Center for Theoretical Physics, Korea)
- *Computational Approaches to Magnetic Systems*
  International Workshop: August 22 – 25, 2023
  – 47% of the workshop budget contributed by the APCTP (Asia Pacific Center for Theoretical Physics, Korea)

- *Condensed Matter Solitons*
  International Workshop: June 28 – 30, 2023
  – 7% of the workshop budget contributed by the KPS (Korean Physical Society, Korea)
- *Dynamics Days Asia Pacific12 (DDAP12)*
  International Workshop: Nov. 7 – 11, 2022
  – 20% of the workshop budget contributed by the KPS (Korean Physical Society, Korea)
- *Advances in the Physics of Topological and Correlated Matter*
  International Workshop: September 19 – 23, 2022
  – 77% of the workshop budget contributed by the IBS HQ, IBS CALDES, APCTP (Asia Pacific Center for Theoretical Physics, Korea), and KPS (Korean Physical Society, Korea)
- *Computational Approaches to Magnetic Systems*
  International Workshop: August 17 – 19, 2022
  – 53% of the workshop budget contributed by the APCTP(Asia Pacific Center for Theoretical Physics), DIME (Daejeon Tourism Organization, Korea), and KPS (Korean Physical Society, Korea)

3.1.5 Advanced Study Group Reports

Spin-orbit coupling in transition metal complexes: from model to realistic system

Convener: Bongjae Kim

This ASG meeting, held from 17–21 February 2025, continued our tradition of fostering collaboration in computational studies of quantum materials, with particular emphasis on systems where spin–orbit coupling plays a key role. A total of 13 ASG members and 11 guest participants joined the event, engaging in active and productive discussions.

List of participants:

ASG members:

Bongjae Kim (Convener, Kyungpook National University)
Heung-Sik Kim (Kangwon National University)
Chang Jong Kang (Chungnam National University)
Ara Go (Chonnam National University)
Sooran Kim (Kyungpook National University)
Hee Chul Park (Pukyong National University)
Se Young Park (Soongsil University)
Minjae Kim (Korea Institute for Advanced Study)
Jae-Ho Han (Korea Advanced Institute of Science and Technology)
Kyoo Kim (Korea Atomic Energy Research Institute)
Choong Hyun Kim (Korea Institute for Advanced Study)
Beom Hyun Kim (Seoul National University)
Kyung-Hwan Jin (Jeonbuk National University)
Kyung Min Kim (IBS Center for Theoretical Physics of Complex Systems)

Guest Members:

Young Woo Choi (Sogang University)
Bo Gyu Jang (Kyunghee University)

Hongkee Yoon (Kangwon National University)
Sungkyun Choi (IBS-vdWQS)
Hong Chul Choi (POSTECH)
Hosub Jin (Ulsan National Institute of Science and Technology)
Jeongwoo Kim (Incheon National University)
Jaewook Kim (KAERI)
Youngjae Kim (KIAS)
Wooil Yang (KIAS)
Jin Soo Park (POSTECH)

Discussion and Collaborations

During the ASG, active discussions were held on various aspects of correlation effects, magnetism, and spin–orbit coupling in a broad range of solid-state systems. Several new collaborations were initiated, while ongoing projects were further advanced with valuable input from ASG participants and guest members. Key discussion topics included:

Quantification of Coulomb parameters:

- Machine learning–based prediction of Coulomb parameters in correlated systems
- Use of physically interpretable ML methods on limited datasets ($\sim$ 50 samples) to predict key interaction parameters
- Comparison of methodologies for quantifying Coulomb parameters and assessing their reliability
- Possible integration of spin–orbit coupling effects into parameter estimation
- Influence of longer-range interactions on electronic, magnetic, and lattice properties

Numerical tools:

- Development of advanced numerical techniques for multi-orbital systems
- Application of machine-learning–assisted, configuration-interaction–based impurity solvers within dynamical mean-field theory
- Exploration of tensor-network–based impurity solvers employing complex-time evolution
- Techniques for describing time evolution in solid-state systems

Lattice action:

- Advances in the understanding of one-dimensional charge-density-wave (CDW) systems
- New approaches for modeling electron–phonon interactions
- Coupling between lattice dynamics and other degrees of freedom, and their connection to recent experimental findings

Theoretical Challenges of Quantum Magnets with Complex Anisotropies
Conveners: Bruno Tomasello, Tim Ziman

The Advanced Study Group (ASG) *Theoretical Challenges of Quantum Magnets with Complex Anisotropies* was convened at the PCS-IBS in Daejeon from 11 May to 7 June 2025 by coordinators Bruno Tomasello and Tim Ziman. Its primary aim was to tackle key open problems in quantum magnets whose behaviour transcends models of collinear ordering and standard spin-wave excitations.

A central inspiration came from the rich phenomenology of rare-earth garnets—magnetic insulators of the form $RE_3M_5O_{12}$, where RE denotes a rare-earth ion and M typically an iron-group element. In these systems, localized 4f electrons on RE sites experience strong, low-symmetry crystal fields, giving rise to highly anisotropic single-ion behaviour and multipolar character. The competition between crystal-field anisotropies and exchange interactions stabilizes complex spin textures such as non-collinear "umbrella" states, frustrated configurations, and field-tuneable orders. Theoretical challenges include modelling systems with symmetry-inequivalent rare-earth sites within large magnetic unit cells, and bridging atomistic and effective low-energy approaches in systems where Kramers vs. non-Kramers character and lattice geometry play essential roles. The ASG aimed to clarify these complex interactions through focused group discussion, shared model-building, and comparisons with experimental results—particularly those related to terbium iron garnet ($Tb_3Fe_5O_{12}$, TbIG) and terbium gallium garnet ($Tb_3Ga_5O_{12}$, TGG). These materials offer concrete testbeds for phenomena such as field-enhanced spin Seebeck effects, magnon band flattening, or topological thermal transport arising from entangled multipolar excitations.

The ASG also explored connections between rare-earth magnetism and broader contexts such as spintronics, topological transport, disorder-induced localisation, and flat bands, promoting the cross-pollination of ideas across scales and disciplines. The ASG was explicitly inclusive and self-assembling. Instead of a rigid, pre-set program, we adopted a dynamic, participant-driven format: short "spark" talks, informal focused discussions, and working groups unfolded alongside ample personal research time. Initial framing discussions—led by core participants (Tomasello, Ziman, Mori, Utesov, Andreanov)—naturally gave way to emergent topics and schedules as further visitors (Slevin, S.K. Kim, Yamamoto, Ohtsuki, K.M. Kim) and PCS scientists joined in. This evolving structure kept engagement high, allowing themes to crystallise organically, from three-magnon vertex models to magnon decay, surface-spin-wave topology, and altermagnetic ordering.

Each week balanced four elements:

1. Dedicated personal research time
2. Spontaneous and scheduled informal discussions
3. One seminar for all PCS staff and one separate ASG-only discussion
4. Joint lunches and social moments

This rhythm of depth and openness created a fertile environment. By the end of four weeks, participants had not only identified new collaborative directions but also sharpened their own research agendas—returning to their home institutions with fresh tools, concrete project plans, and lasting professional and personal connections.

Week 1

The first week was shaped by a progressive convergence of thematic directions—ranging from rare-earth garnets to Kagome metals with 4f electrons—and grounded in productive personal research and focused informal exchange. Early discussions revisited key techniques such as the triangular linear method for spectral function calculations, applied to 2D lattices. These linked to Bruno Tomasello's ongoing work on density-of-states calculations and later connected to broader debates on magnetic excitations in non-collinear rare-earth systems.

The ASG "Theoretical Challenges of Quantum Magnets with Complex Anisotropies" was officially opened by Bruno Tomasello's introduction on Tuesday afternoon, setting the tone for a collaborative and inclusive four-week programme. It encouraged a self-organising format of informal talks, joint discussions, and focused research, with the aim to seed new collaborations, refine theoretical tools, and identify open questions emerging at the intersection of quantum magnetism and anisotropic phenomena. The introduction evolved into an informal talk and round-table discussion with PCS scientists about the interplay between crystal-field effects, spin–orbit coupling, and topological magnetism, framing the ASG as a space for open exploration, from rare-earth systems to spintronics and beyond.

A significant thread emerged around Kagome metals hosting rare-earth ions, which present a platform for exploring the interplay between itinerant electrons and highly anisotropic local moments. Discussions clarified distinctions between vanadium- and manganese-based systems, the role of Kondo-type exchange in hybrid Kagome layers, and how spin–orbit coupling or internal fields deform the flat-band structures. These debates led to renewed interest in spin-anisotropic Hamiltonians and potential topological responses, as signaled by recent literature. Concurrently, the group revisited theoretical models of rare-earth iron garnets. Here, crystal-field-driven anisotropies and complex spin textures (e.g., umbrella states) were examined both through semiclassical treatments and perturbative approaches based on Stevens' operators. These themes laid the foundation for later work on spin Seebeck physics and magnon decay.

The week's PCS informal seminar was given by Michiyasu Mori, titled "Basic theoretical physics of the Spin Seebeck Effect." It offered a pedagogical arc—from foundational spin Seebeck mechanisms in insulating magnets to a focused presentation of recent theoretical results on $Tb_3Fe_5O_{12}$ (TbIG). The study, co-authored with Tomasello and Ziman, shows how crystal-field excitations on inequivalent Tb sites account for the anomalous low-temperature magnetic-field dependence of the SSE. The discussion addressed both microscopic modelling and macroscopic thermoelectric response, engaging participants from PCS and the ASG in detailed questions about anisotropy, field perturbations, hysteresis, and tensorial response from the quantum states of the single ions.

ASG members: B. Tomasello, M. Mori, T. Ziman, A. Andreanov, O. Utesov

Week 2

The second week of the Advanced Study Group deepened the scientific focus while broadening its collaborative landscape. Early in the week, discussions centred around rare-earth garnets and the role of anisotropy, with Keith Slevin and Se Kwon Kim joining the group and contributing to several exchanges. Topics ranged from magnon transport to disorder-driven effects in insulating magnets. Keith proposed considering static and dynamic disorder in the context of garnet physics, while Se Kwon's background in ultrafast phenomena and spintronics opened further bridges between topological and dynamical aspects of magnetic response.

Tuesday featured the open PCS seminar "Exotic magnonic transport in 2D magnets" by Se Kwon Kim, who presented recent work on topological magnons and spin transport. His talk stimulated strong interaction, especially regarding magnetization dynamics and its coupling to band topology. Follow-up discussions addressed the potential role of rare-earth-induced anisotropy in controlling topological regimes—an emerging motif of the ASG. Collaborative ideas involving Se Kwon, Tim, and others began to take shape, especially around extending these ideas to low-energy crystal-field-dominated systems.

Meanwhile, internal progress continued on the theoretical side. Independent work advanced on methods for computing spectral properties in 2D systems with nontrivial unit cells, and planning intensified around multiband kagome models decorated by rare-earth layers. The idea of hybridising conduction-electron degrees of freedom with localised anisotropic 4f moments—potentially modifying the effective gauge structure—was revisited, particularly considering recent studies on quantum Hall phases in rare-earth kagome magnets. A practical thread followed the spin-motive-force formalism, guided by a PhD thesis shared by Michiyasu Mori, laying groundwork for further discussions upon his return.

An informal session on Friday led by Oleg Utesov explored the formation of Skyrmion lattices in tetragonal frustrated systems with dipolar interactions. Oleg's analytical treatment of semi-classical spin textures—driven by temperature and field variation—drew connections to rare-earth systems and flat-band phenomena. This opened a dialogue on how quantum effects and anisotropic single-ion physics might deform or stabilise such textures. The numerical component of the work was carried out by Kyoung-Min Kim, whose detailed contributions sparked a stimulating exchange on simulation techniques, including the treatment of boundary conditions and the scalability of numerical models. This interplay between analytical insight and computational implementation enriched the session, particularly in light of ongoing ASG themes on the crossover between classical textures and quantum anisotropic effects.

ASG members: K. Slevin, S.K. Kim, B. Tomasello, T. Ziman, A. Andreanov, O. Utesov, K.M. Kim

Week 3

Week three was marked by a surge in collaborative energy and definition of ideas. The arrival of Kei Yamamoto and the return of Michiyasu Mori added critical mass to the group, with the topics of magnon vertex models, spin Seebeck physics, and kagome metals evolving in new directions. Early in the week, informal discussions explored how vertex-type many-body interactions in anisotropic magnets could account for the spectral broadening of magnons observed in experiments. A collaborative model was seeded—drawing on non-collinear spin textures and cubic corrections to the Hamiltonian—and refined through joint work between Mori, Ziman, and Tomasello. Later during the week, analytical work on vertex corrections and low-energy expansions were treated, with further derivations to be developed post-ASG.

On Monday afternoon Keith Slevin led an informal ASG discussion on the Anderson transition and disorder-induced localization. The clear exposition of tight-binding models, finite-size scaling, and the application of machine learning to critical phenomena allowed anticipation of Tomi Ohtsuki's PCS talk of Week 4. The talk sparked dynamic exchange with participants and laid groundwork for possible cross-pollination. The discussion opened a potential bridge between quantum localization and driven condensed-matter systems.

On Wednesday afternoon, Alexei Andreanov led an informal ASG discussion on the origins and classification of flat bands in photonic, magnetic, and electronic systems. Starting from symmetry-enforced constraints in kagome and pyrochlore lattices, the conversation explored how local interference mechanisms generate compact localized modes, and how such flat bands differ fundamentally from dispersionless crystal-field excitations. We examined hybrid scenarios where strongly anisotropic single-ion states couple to exchange-driven modes, potentially lifting degeneracies and introducing controlled dispersion. The session helped clarify the distinctions between geometric flat bands and those arising from local degrees of freedom, setting a useful framework for ongoing ASG discussions.

On Thursday Kei Yamamoto gave a PCS seminar on "Topological characterisation of magnetostatic surface spin waves." Using a modern formalism, he connected classical Damon–Eshbach theory with topological edge modes in magnets dominated by dipolar interactions. The discussion opened compelling questions about robustness, classification, and symmetry breaking in long-range interacting systems. The audience engaged with stimulating questions and commentary, helping to ground the mathematical developments in physical intuition.

On Wednesday, the group visited KAIST at the invitation of Se Kwon Kim. The institutional tour, group lunch, and museum visit provided a memorable social highlight. Throughout the week, personal research progressed in parallel. On Friday, after an internal PCS seminar on polariton theory, the group returned to spin Seebeck physics followed by a focussed session to coordinate contributions to a joint paper. A discussion with Boris Altshuler and Keith Slevin also took place, focusing on coercivity and hysteresis in ferro- and antiferromagnets. The week concluded with a gathering, where ASG-themed 'artwork' became a creative medium for reflection and exchange, and some goodbyes.

ASG members: K. Slevin, S.K. Kim, B. Tomasello, T. Ziman, A. Andreanov, O. Utesov, K. Yamamoto

ASG visitor: Kyongmo An

Week 4

The final week of the ASG was marked by an overall shift from collective experimentation to more focused, project-driven work. Discussions centred on how vertex-type interactions in non-collinear magnets can be incorporated into magnon theories, aiming to bridge semi-phenomenological approaches with symmetry-based constraints. These discussions framed a pathway for future collaborative modelling of broadened spin-wave spectra. Tuesday, although a national holiday, allowed for unstructured yet productive engagement. Independent reading and talk preparation were complemented by an extended exchange with PCS scientists, who shared frameworks for treating spin dynamics in open quantum systems via linear-response approaches. These methods resonate with broader ASG themes around quantum dissipation and magnonic transport. On Wednesday, independent work dominated the early day; however, an informal PCS blackboard session by Oleg Utesov provided a useful return to diagrammatic methods, revisiting Green's functions and time ordering in non-equilibrium settings.

Thursday offered formal closure. The morning seminar by Bruno Tomasello at KAIST, hosted by Se-Kwon Kim, provided a platform to present recent work on TbIG and TGG. The focus was on pedagogical clarity—linking crystal-field mechanisms, sublattice anisotropies, and field-tuned excitations. In the afternoon, Tomi Ohtsuki's seminar at PCS introduced machine learning techniques for identifying and classifying topological quantum phases. His exploration of weak-measurement dynamics and quantum algorithms prompted a lively and broad discussion. The day ended with informal remarks and a final PCS moment together, bringing together core ASG members and local participants in a relaxed but content-rich setting.

Although Friday was a national holiday, scientific discussions continued at PCS. A long exchange with Alexei Andreanov explored how evolving constraints in frustrated spin systems might lead to glass-like dynamics, raising theoretical questions around ergodicity breaking, relaxation mechanisms, and time-scale separation.

ASG members: T. Ohtsuki, K. Slevin, B. Tomasello, T. Ziman, A. Andreanov, O. Utesov

ASG visitor: Jean-Yves Fortin

Low-dimensional magnetism and quantum phenomena from computational perspectives
Convener: Heung-Sik Kim

This ASG meeting, held from the 19th to 23rd of August 2024, aimed to accelerate collaboration on computational studies on magnetism and related phenomena in strongly correlated materials including transition metal oxides and chalcogenides. During the meeting, there were active discussions about the collaborations on the role of electron correlations and flat bands in Kagome and related systems. Additionally, three guest members delivered talks on superconductivity, magnetism, and dynamics in low-dimensional magnetic systems. Below we list the participants and describe details of scientific discussions and collaborations during this meeting.

List of participants:

ASG members:
Heung-Sik Kim (Convener, Kangwon National University)
Chang Jong Kang (Chungnam National University)
Ara Go (Chonnam National University)
Sooran Kim (Kyungpook National University)
Bongjae Kim (Kyungpook National University)
Hee Chul Park (Pukyong National University)
Se Young Park (Soongsil University)
Minjae Kim (Korea Institute for Advanced Study)
Jae-Ho Han (Korea Advanced Institute of Science and Technology)
Kyoo Kim (Korea Atomic Energy Research Institute)
Choong Hyun Kim (Korea Institute for Advanced Study)
Hyeong Jun Lee (Korea Advanced Institute of Science and Technology)
Beom Hyun Kim (IBS Center for Theoretical Physics of Complex Systems)
Kyung Min Kim (IBS Center for Theoretical Physics of Complex Systems)

Guest Members:
Jun Sung Kim (POSTECH)
Kyong Hwan Jin (Jeonbuk National University)
Jeongwoo Kim (Incheon National University)
Jaewook Kim (Korea Atomic Energy Research Institute)
Minu Kim (Chung-Ang University)
Bo Gyu Jang (Kyunghee University)
Hong Chul Choi (POSTECH)
Hosub Jin (Ulsan National Institute of Science and Technology)
Hyun-Yong Lee (Korea University at Sejong)

Collaborations

Electron correlations in flat bands from Kagome geometry

During this ASG meeting, we discussed the role of electron correlations in Kagome lattices consisting of transition metal elements, especially on the effects of on-site Coulomb repulsion and Hund's coupling in flattening the bandwidth of Kagome-induced geometrically frustrated bands. On this subject, Heung-Sik gave an IBS seminar talk on the correlation-induced flat bands in a Mn-based Kagome compound $Sc_3Mn_3Al_7Si_5$, presenting an example of the collaboration between the geometrical frustration and electron correlation on realizing flat dispersions in the vicinity of the Fermi level. It has been proposed that the dynamical nature of the electron correlation and the interorbital hybridization are crucial in realizing the flat dispersions in transition metal-based Kagome systems. Subsequent discussions and collaborations are ongoing to search for other correlation-induced flat band systems and their potential consequences including charge-density waves and magnetism.

Numerical tools for the role of Hund's coupling in multiorbital correlated systems

From previous and current ASG meetings, it has been demonstrated that Hund's coupling in transition metal-based multiorbital systems gives rise to several novel phenomena, including orbital decoupling and the promotion of flat bands in $Sc_3Mn_3Al_7Si_5$, unconventional electronic structures and magnetism in ruthenium-based oxides, and unique transport features in osmate compounds. Therefore, the development of appropriate numerical tools to capture the essence of multiorbital physics driven by Hund's coupling is essential. In addition to the currently available quantum Monte Carlo-based impurity solver used in dynamical mean-field theory calculations, we are initiating a collaboration to develop and apply new quantum impurity solvers to study the low-temperature limit of multiorbital problems during this ASG meeting. Specifically, a new tensor-network-based impurity solver, utilizing complex time evolution methodologies, is being developed and tested. This solver will be benchmarked against the configuration-interaction-based method developed by ASG members.

Discussions with guest scientists

Quantum materials for electronically isolated topological fermions

During his stay, Prof. Jun Sung Kim presented a talk on his current progress in realizing systems with high anomalous Hall angles for efficient spintronic devices. In addition, he showed several results on the fermiology and transport measurement results of layered compound $PdCrO_2$ and other related systems, especially focusing on the emergence of anomalous Hall conductivity above Néel temperature by the short-ranged Cr spin correlations with finite spin chirality. Subsequent discussions posed many interesting questions on the nature of short-ranged magnetic orders and computational methods to treat such dynamic effects.

Superconductivity in (Ba,K)SbO_3

During his visit, Prof. Minu Kim gave a talk on the superconductivity of (Ba,K)SbO_3, a related system to the well-known superconductor (Ba,K)BiO_3, where the nature of superconductivity and charge-density wave order remains unclear. To shed light on this, Prof. Kim synthesized potassium-doped $BaSbO_3$ using high-pressure synthesis techniques and demonstrated that strong bonding between oxygen and metal atoms plays a more critical role in superconductivity in these materials than specific charge characteristics. The subsequent discussions led to several potential collaboration themes between ASG members and Prof. Kim's group.

Study of quantum dynamics via tensor networks

Prof. Lee's talk was on the quantum thermalization and quantum dynamics of the dipolar Bose-Hubbard model studied via tensor network method. It was shown that, at half-integer filling, the ground state forms a charge density wave. The Hamiltonian dynamics are significantly constrained and exhibit a lack of thermalization over extended periods due to the emergence of quantum scar states. His talk and subsequent discussions showed that tensor network method can be a useful tool for the study of dynamics of quantum materials.

Coherent Charges, Spins and Phonons in Superconducting Weak Links
Convener: Robert Shekhter
Co-conveners: Hee Chul Park, Sunghun Park

The Advanced Study Group (ASG) was active throughout the calendar year 2024, during which its activities followed the approved research plan. Collaborative efforts during two meetings on-site at PCS were complemented by individual work of the ASG members during the year 2024 and regular online activity. Research carried out within the ASG has resulted in a number of papers, published, submitted, or prepared for publication (refs. [1–7]). The three most significant scientific achievements, in our opinion, are the following:

1. Nanomechanical shuttling of superconducting "flying" charge qubits (suggested in [1–2]) as a tool for quantum communication;
2. Realization of quantum communication between superconducting charge qubits via nanomechanical "Schrödinger cat states" was demonstrated [3–5];
3. Coherent spintronics of spin-orbit-active superconducting and normal electric weak links was suggested and studied in [6–7].

Reviews of the ASG research activity, following the directions stated in the approved Research Plan, are presented below.

1. Nanomechanical shuttling of superconducting "flying" charge qubits [1–2]

A new concept of shuttling "flying" charge qubits was formulated within the framework of our study on superconducting nanomechanics. The system under our consideration was a nanomechanical superconducting single-electron transistor device. In such a device, the mechanical displacement of a charged superconducting dot with respect to an attached pair of superconductors is controlled by two forces originating from both Josephson and Coulomb couplings of the dot to the electrodes. A nontrivial fact is the quantum indefiniteness relation between the above two forces, which introduces interplay between quantum fluctuations of the electric charge located on the dot. This interplay qualitatively modifies the nanoelectromechanics of the charge qubit's oscillatory motion in the device, providing a new type of quantum qubit information transfer between superconductors that we refer to as the shuttling of superconducting flying qubits.

We have formulated the equations describing both nanomechanical semiclassical motion of the shuttle and quantum fluctuations of the charge located on it. Also, we analytically demonstrated a new phenomenon of nanomechanical instability of a movable dot with respect to the onset of spatial oscillatory displacement (shuttling). Ongoing research is focused on the numerical study of the development of this shuttle instability in two spatial dimensions, with the goal of demonstrating the possibility of controlling the shuttle trajectory electrostatically. Research will be continued.

2. Communication between superconducting charge qubits via nanomechanical "cat states" [3–5]

Quantum networks are the core element of quantum computers. They provide communication between individual qubits, enabling the formation of a particular type of entanglement. In our research, we considered a quantum network consisting of two CPBs coupled to a nanomechanical subsystem represented by the bending mode of a nanowire. We described the manipulation of such a network which allows transducing quantum information between charge qubits via an intentionally built superposition of nanomechanical coherent states, the cat state. Two projects were carried out to explore single or multiple nanomechanical cat states for such communication and are listed below.

2a. Nanomechanical manipulation of superconducting charge-qubit quantum networks [3]

In this project we suggested a nanoelectromechanical setup and a corresponding time protocol for controlling parameters in order to demonstrate nanomechanical manipulation of superconducting charge-qubit quantum network. We illustrate it on an example reflecting an important task for quantum information processing—the transmission of quantum information between two charge qubits facilitated by nanomechanics. The setup is based on terminals utilizing the AC Josephson effect between bias voltage-controlled bulk superconductors and mechanically vibrating mesoscopic superconducting grain in the regime of the Cooper pair box, controlled by the gate voltage. The described manipulation of a quantum network is achieved by transduction of quantum information between charge qubits and intentionally built nanomechanical coherent states, which facilitate its transmission between qubits. This performance is achieved using quantum entanglement between electrical and mechanical states.

2b. Two-dimensional nanomechanical cat states generated by a voltage-driven Cooper pair box: engineering of controlled nanomechanical two-dimensional motion [4]

The research, done in this direction, resulted in the proposal of a nanoelectromechanical setup that generates a particular type of motion—the circular motion of a mesoscopic superconducting grain, described by entangled nanomechanical coherent states. The setup is based on a mesoscopic terminal utilizing the AC Josephson effect between the superconducting electrodes and the grain, operating in the regime of the Cooper pair box controlled by the gate voltage. The grain is placed on the free end of the suspended cantilever, performing controlled two-dimensional mechanical vibrations. Required functionality is achieved by operating two external parameters, bias voltage between the superconducting electrodes and voltage between gate electrodes, by which the nanomechanical coherent states are formed and organized in a pair of entangled cat states in two perpendicular spatial directions which evolve in time to provide a circular motion.

2c. Nanomechanical ancilla qubits generator for error correction algorithms in quantum computation [5]

The aim of our study was to suggest a nanoelectromechanical setup that generates properly entangled ancillary ("ancilla") qubits for error correction algorithms in quantum computing, which was demonstrated as an encoder for the three-qubit bit-flip code. The setup is based on a mesoscopic terminal utilizing the AC Josephson effect between voltage-biased superconducting electrodes and a mechanically vibrating mesoscopic superconducting grain in the regime of the Cooper pair box, controlled by the gate voltage. The required functionality was achieved by a specifically tailored time protocol of operating two external parameters: bias voltage and gate voltage. The superconducting grain is fixed on the free end of a cantilever, performing controlled in-plane mechanical vibrations, generating the nanomechanical coherent states, organized in a pair of entangled cat states in two perpendicular spatial directions. The Cooper pair box and the nanomechanical coherent states become three entangled qubits in a particular way: quantum information, initially encoded in a superposition of the Cooper pair box states, is transduced into the quantum superposition of two special 3-qubit entangled states, $|\uparrow ++\rangle$ and $|\downarrow --\rangle$. It mainly serves for error correction, "installed" on a single physical object in which the last two ancilla qubits are generated.

3. Coherent spintronics of spin-orbit (SO) active superconducting and normal electric weak links [6–7]

3a. Spin-polarization of Cooper pairs tunneling through SO-active superconducting weak link [6]

On a fundamental level, the electric and magnetic properties of solids are determined by two basic properties of electrons: their charge and their spin. While on mesoscopic length scales quantum coherence dominates charge- and spin phenomena, making room for quantum electronics and quantum spintronics, macroscopic quantum coherence in metals is due to a superconducting ordering of electrons. The role of the electronic spin in the appearance of superconductivity is decisive since it is the spin-$\frac{1}{2}$ of electrons that makes them fermions and allows for the Cooper instability of the Fermi surface, the pairing of electrons, and the condensation of these Cooper pairs into a macroscopically coherent ground state.

If one asks how macroscopic coherence affects charge- and spin phenomena in BCS superconductors, one finds, however, a great asymmetry. Many superconducting features, such as nondissipative electric currents, Meissner screening of magnetic fields, vortex superconductors, weak superconductivity, and the Josephson effect, demonstrate how charge currents are strongly modified. On the other hand, no spin currents or other manifestations of spin coherent phenomena appear in BCS superconductors. This is because in a BCS superconductor the Cooper pairs form spin-singlet states and hence are "locked" into a state that carries no spin. The question of how one may "unlock" or spin-polarize the Cooper-pair spins is the main focus of our study.

We employ the electron spin-orbit interaction to show how electron spins can be manipulated in a nonmagnetic BCS weak link. We find that spin polarization of Cooper pairs is induced in the point contact. Such spin polarization affects a charge supercurrent flowing through the Josephson weak link. Finite magnetization of the superconductor is maintained if spin-orbit interaction varies in time, which destroys a time reversal symmetry of the system. We are currently studying this effect for the particular case of a microwave-electric-field-induced Rashba spin-orbit coupling. We have demonstrated that a circularly polarized microwave induces time-independent magnetization, making possible a magnetic proximity phenomenon in a SOI-active superconducting weak link.

3b. Controlling spin accumulation in a quantum dot by the AC Rashba spin-orbit interaction [7]

Tunneling transport of electrons in nanodevices offers an exceptional tool for accumulation and control of electric charge in nanometer-sized conductors. Pronounced mesoscopic phenomena, such as resonant tunneling of electrons and single-electron tunneling, make such control achievable electrostatically. Electronic spin—a complementary fundamental property to the electronic charge of electrons—can also be activated in tunneling devices due to the phenomenon of spin-dependent tunneling, opening a direction of spintronic phenomena in nanodevices. One example has to do with the possibility to accumulate a controllable spin in a nanometer-sized quantum dot.

An obvious way to involve the electronic spin in tunneling transport is to employ magnetic materials to build hybrid nanodevices, which allow for magnetic control of spintronic phenomena. Such control appears to be more difficult as compared with an electrostatic one used for manipulation of electric charge. The reason is the difficulty to spatially localize the magnetic fields on a nanometer length scale and in achieving selective control in hybrid nanodevices. The possibility of non-magnetic activation of the electronic spin degree of freedom in nanostructures would serve as a way to avoid this problem.

One way to achieve non-magnetic tuning of the electronic spin would be to employ the spin-orbit interaction, located at the tunneling electronic weak links which allows the electronic spin to be affected by an external electric field. Spin polarization of the electrons, which occurs due to electronic tunneling via SOI-active weak link, could be expected to allow for electric generation of the magnetization of a small-sized nonmagnetic device. However, a constraint originating from the time reversal symmetry of SOI prohibits any effect of SOI on two-terminal tunneling of electrons in non-superconducting devices. The only way to revive the role of SOI in electronic transport is therefore to break the time reversal symmetry of spin-orbit interaction.

In this project we have suggested to employ time-dependent electric fields, generating Rashba SOI, to destroy the time reversal symmetry of the spin-orbit coupling. We have shown that a time-dependent Rashba interaction results in spin polarization of tunneling electrons, allowing the accumulation of a controllable magnetization in nonmagnetic single-dot tunneling devices. Control of the resulting magnetization of the dot can be achieved by tuning the polarization of the AC electric field responsible for SOI Rashba interaction (from circular to linear), by changing the applied bias voltage, and by varying the degree of a gate voltage-induced asymmetry of the device.

3c. Thermoelectricity in systems driven by spin-orbit coupling induced by AC electric fields [8]

The system we have studied in this project contains a single-level quantum dot coupled to left and right reservoirs via weak links in which the Rashba spin-orbit interaction is active. In our approach we have used the Keldysh Green's function formalism to calculate the particle and energy fluxes. To investigate the thermoelectric properties, the linear response theory has been adopted, where the relevant thermoelectric coefficients are defined in response to chemical potential and temperature differences (in linear order). Importantly, although the time-driven Rashba coupling breaks the time reversal symmetry in the system, the Onsager reciprocal relations hold in our system. The unique features of the response coefficients—namely, the conductance, the Seebeck coefficient (S), and the electronic thermal conductance (κ_e)—are inspected. For good thermoelectricity, we look for materials with high Seebeck coefficient and low thermal conductance. Our results show that in the presence of SOC, the system exhibits enhanced thermoelectricity. In the next step, we have discussed possible efficiencies (for a heat engine and a heat pump) in our system, showing that in the presence of SOC, the maximum one achieves is the Carnot efficiency, although the presence of SOC enhances the efficiency more than the absence of it.

In addition to the activity listed above, a number of formal and informal meetings, both in online and offline formats, took place during the year 2024. Finally, we would like to note that our work at the PCS would have been significantly less productive without the greatly appreciated support and very efficient assistance from the director of the center, Prof. Sergej Flach, the visitors program coordinator Dr. Jung-Wan Ryu, his assistants Ms. Jaehee Kwon and Ms. Gileun Lee, Yunjin Heo, as well as all other staff and technical support members.

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Entanglement and Dynamics in Quantum Matter
Convener: Yong Baek Kim

In order to facilitate further collaborations with the IBS-PCS members and the researchers at KAIST and POSTECH, I brought three graduate students (Emily Zhang, Daniel Schultz, Felix Desrochers) and one postdoctoral fellow (SangEun Han) in my research group at the University of Toronto to the IBS-PCS. During this period, I conducted research with them on non-Fermi liquids, electric-field-induced quantum spin liquid phases, and thermal Hall conductivity in frustrated magnets. We also had extensive discussions with Dung Nguyen Xuan, Bum Hyun Kim, and other members at the IBS-PCS.

On June 21, we had a mini-workshop by bringing many junior researchers from the IBS-PCS, KAIST, and POSTECH as well as four researchers from the University of Toronto. The speakers were three from IBS-PCS, three from Sungbin Lee's group at KAIST, two from Gil Young Cho's group at POSTECH, one from Eun-Gook Moon's group at KAIST, and four from the University of Toronto. We had extensive discussions on various topics, which included:

- Topological phases in non-Hermitian systems
- Magnetism on twisted bilayer graphene dots
- Proximate Kitaev systems in in-plane magnetic field
- Geometric frustration and Kitaev physics in frustrated magnets
- Electric-field-tuned quantum spin liquids
- Dipolar–Octupolar quantum spin ice
- Quantum impurity models for two-stage Kondo destruction phase transitions
- Generalized 3D stabilizer codes
- Correlated phases in transition metal dichalcogenides
- Variational Monte Carlo study of frustrated magnets
- Non-Hermitian quasicrystals
- Monolayer Kagome metal

Prof. Eun-Gook Moon and Prof. Sungbin Lee also attended the mini-workshop. All of us had discussions on various aspects of the topics listed above. It was a very fruitful event, and I expect that further collaborations will emerge out of these activities. For example, we already have ongoing collaborations on quantum spin liquids and higher-form symmetry breaking with Gil Young Cho and Dung Nguyen Xuan.

Computational study on strongly correlated low-dimensional magnetic systems
Convener: Chang-Jong Kang

The ASG meeting, held from 28 August 2023 to 29 August 2023, aims to accelerate international collaboration among experts in the field of strongly correlated systems. Listed below is a list of the participating scientists. Additionally, we briefly describe the activities during the ASG meeting.

Participants:

ASG members:

1. Chang-Jong Kang (Chungnam National University, convener)
2. Bongjae Kim (Kunsan National University)
3. Kyoo Kim (KAERI)
4. Sooran Kim (Kyungpook National University)

Domestic participants:

5. Sung-Hoon Lee (Kyung Hee University)
6. Beom Hyun Kim (PCS-IBS)
7. Jae-Ho Han (PCS-IBS)
8. Hong Chul Choi (MPK POSTECH)

International participants:

9. Alessandro Toschi (TU Wien, Austria)
10. Giorgio Sangiovanni (University of Wuerzburg, Germany)
11. Michele Reticcioli (University of Vienna, Austria)
12. Lorenzo Celiberti (University of Vienna, Austria)

Collaboration on osmate compounds: Material differentiation between $NaOsO_3$ and $LiOsO_3$

In this project, we discussed the origin of the strikingly different spectroscopic properties of the chemically similar compounds $NaOsO_3$ and $LiOsO_3$. According to many-body computations using density functional theory plus dynamical mean-field theory, we have demonstrated that the highly sensitive physics of these two materials is controlled by their proximity to an adjacent Hund's-Mott insulating phase. Although $5d$ oxides are mildly correlated, we found that the cooperative action of intraorbital repulsion and Hund's exchange becomes the dominant physical mechanism in these materials when their t_{2g} shell is half filled. These small material-specific details result in an extremely sharp change of the electronic mobility, explaining the surprisingly different properties of the paramagnetic high-temperature phases of the two compounds.

Discussions with guest scientists:

Jahn-Teller polaron in the spin-orbit multipolar magnetic oxide Ba_2NaOsO_6 (presented by Lorenzo Celiberti)

Complex oxides hosting $5d$ electrons present a variety of exotic phases arising from spin-orbital (SO) interactions and electronic correlation (EC). In the Mott insulator Ba_2NaOsO_6, a canted antiferromagnet with multipolar interactions, strong EC together with Jahn–Teller (JT) lattice activity pave the way for bridging polarons and SO coupling, distinct quantum effects that play a critical role in charge transport and spin-orbitronics. Polarons are quasiparticles originating from strong electron–phonon interaction and are ubiquitous in polarizable materials, especially in $3d$ transition metal oxides. Despite the more spatially delocalized nature of $5d$ electrons, we demonstrate the formation of Jahn–Teller spin–orbital polarons in electron-doped $Ba_2Na_{1-x}Ca_xOsO_6$ by combining *ab initio* calculations with nuclear magnetic resonance and muon spin rotation measurements. The polaronic charge trapping process converts the Os $5d^1$ spin–orbital $J_{\text{eff}} = 3/2$ levels, characteristic of pristine BNOO, into a $5d^2$ $J_{\text{eff}} = 2$ manifold, leading to the coexistence of different J_{eff} states in a single-phase material. Moreover, we suggest that polaron formation creates robust in-gap states that prevent the transition to a metallic phase even at ultrahigh doping, thus preserving the Mott gap across the entire doping range from d^1 Ba_2NaOsO_6 to d^2 Ba_2CaOsO_6.

Tensor Network Approaches to Many-Body Systems
Convener: Hyun-Yong Lee, Seung-Sup Lee

1. Outline

In accordance with the ASG plan, our initial meeting occurred at IBS PCS from July 10 to July 21, 2023. The meeting's activities can be categorized into two primary components. Firstly, all ASG members gave seminar-style presentations, sharing their projects and recent accomplishments in the realms of strongly correlated systems, tensor networks, and various numerical methods for many-body systems. Secondly, the meeting fostered enthusiastic and dynamic discussions among our members, PCS members, and visitors, which resulted in the establishment of numerous collaborations on various topics.

2. Attendees

Listed below is a list of the participating ASG members.

- Hyun-Yong Lee (Korea University Sejong, 10 July – 21 July)
- Seung-Sup Lee (Seoul National University, 10 July – 21 July)
- Satoshi Morita (Keio University, 10 July – 13 July)
- Chia-Min Chung (National Sun Yat-Sen University, 10 July – 15 July)
- Takafumi Suzuki (University of Hyogo, 10 July – 15 July)
- Tsuyoshi Okubo (University of Tokyo, 10 July – 21 July)
- Ryui Kaneko (Waseda University, 10 July – 21 July)
- Naoki Kawashima (University of Tokyo, 10 July – 18 July)
- Wei-Lin Tu (Keio University, 10 July – 21 July)
- Jheng-Wei Li (LMU Munich, 10 July – 21 July)
- Ying-Jer Kao (National Taiwan University, 10 July – 19 July)
- ShengHsuan Lin (Technical University of Munich, 10 July – 21 July)
- Yun-Tak Oh (Korea University Sejong, 10 July – 20 July)
- Dong-Hee Kim (Gwangju Institute of Science and Technology, 17 July – 21 July)
- Synge Todo (University of Tokyo, 10 July – 12 July, 19 July – 21 July)
- Hong-Hao Tu (Technical University of Dresden, 17 July – 21 July)
- Hee Chul Park (Pukyong National University)

Moreover, we have hosted various guest scientists and graduate students, as listed below:

- Aram Kim (Assistant Professor at DGIST)
- Sunam Jeon (Postdoctoral Researcher at Korea University Sejong)
- Jeon Hyo-Jae (Ph.D Student at Sunkyunkwan University)

- Hoang Anh Le (Ph.D Student at Korea University)
- Jihoon Kim (Ph.D Student at Seoul National University)
- Seongyeon Youn (Ph.D Student at Seoul National University)
- Sanghyun Park (Ph.D Student at Seoul National University)
- Donghoon Kim (Ph.D Student at KAIST)
- Minsoo Kim (Ph.D Student at KAIST)
- Hee Seung Kim (Ph.D Student at KAIST)

3. *Seminar*

Here is the seminar schedule that was organized:

- July 10 Afternoon — *Satoshi Morita:* Ashkin–Teller phase transition and multicritical behavior in a classical monomer–dimer model
- July 12 Morning — *Hyun-Yong Lee:* Dipole condensations in tilted optical lattices
- July 12 Afternoon — *Chia-Min Chung:* Matrix product state simulations of quantum quenches and transport in Coulomb blockaded superconducting devices
- July 13 Morning — *Takafumi Suzuki:* Quantum spin liquid in the Kitaev–Gamma model on a honeycomb lattice
- July 13 Afternoon (PCS seminar) — *Tsuyoshi Okubo:* Quantum–classical entangled approach with tensor networks for spin liquid
- July 14 Morning — *Ryui Kaneko:* Simulating the time evolution of isolated quantum many-body systems using infinite projected entangled pair states
- July 14 Afternoon — *Naoki Kawashima:* Tensor-ring decomposition
- July 17 Morning — *Wei-Lin Tu:* Generating function for projected entangled-pair state
- July 17 Afternoon — *Jheng-Wei Li:* Controlled bond expansion: a rank-adaptive approach for single-site DMRG and TDVP
- July 18 Morning — *Ying-Jer Kao:* Variational tensor network operator
- July 18 Afternoon — *ShengHsuan Lin:* Accessing excited eigenstates of two-dimensional systems with isometric tensor network states
- July 19 Morning — *Yun-Tak Oh:* Rank-2 toric code
- July 19 Afternoon — *Dong-Hee Kim:* Scale and conformal invariance in the long-range antiferromagnetic Ising chain: a VMC+RBM approach
- July 20 Morning — *Synge Todo:* Markov-chain Monte Carlo in tensor-network representation
- July 20 Afternoon (PCS seminar) — *Hong-Hao Tu:* Klein bottle partition function and tensor networks

4. *Collaboration Topics*

1. Wavefunction deformation bridging two critical points
   - After an in-depth discussion with Naoki Kawashima (NK) and Hong-Hao Tu (HH), Hyun-Yong (HY) formulated a tensor network wave function connecting the Ising critical point to another critical point characterized by central charge c = 1. Through this formulation, it is expected that the process of connecting critical points characterized by different universality classes can be analyzed by examining the deform-

ation of the wave functions. Additionally, HH's seminar presented calculations of Klein bottle entropy, which can help identify the critical properties of the intermediate wave functions.

2. Quantum dynamics simulations in a system with center of mass conservation
   - After Ryui Kaneko's (RK) presentation on the quantum dynamics of the Bose-Hubbard model, HY and RK engaged in a profound discussion regarding quantum dynamics simulations in systems where the center of mass is conserved. They explored the implications of the conservation law on quantum dynamics and dis- cussed intriguing results derived from it. Additionally, they searched theoretical approaches, experimental feasibility, and the potential for collaborative research.

3. Evaluation of modular commutator using tensor networks
   - Modular commutator is a recently proposed formula that predicts the central charge, determining the critical properties of a system, using only the ground-state wave function of the system. ShengHsuan Lin's (SL) seminar on Isotropic Tensor Networks sparked HY's interest, and together they brainstormed methods for com- puting the modular commutator based on the insights gained from the seminar. Although there are still unresolved issues, both anticipate that they can address them through collaborative research efforts.

4. Two-dimensional dipolar Bose-Hubbard model
   - After HY's seminar on the 1D dipolar Bose-Hubbard model, Chia-Min Chung (CM) and HY engaged in discussions about the 2D version of this model. They explored approaches using Quantum Monte Carlo methods and field-theoretical methods, as well as discussed the application of tensor network methodologies. They have continued to stay in touch after the ASG meeting, planning to collaborate on further research regarding the 2D model by discussing the strengths and limitations of each methodology.

5. Variational tensor network approach for Kagome antiferromagnet
   - After Ying-Jer's (YJ) presentation on the variational tensor network operator (VTNO), HY and YJ engaged in a thorough discussion about the potential use of VTNO in tackling the well-known problem of the Kagome antiferromagnet ground state in condensed matter physics. We are of the opinion that YJ's classification of the symmetric tensor network provides valuable assistance in constructing an appropri- ate initial state for the VTNO application.

6. Variational uniform matrix product states (VUMPS) approach to heavy fermions
   - Minsoo Kim (MK) and Yun-Tak Oh (YO) have had intensive discussions throughout this ASG meeting. MK has been studying Kondo physics in the context of quantum impurity models such as the Anderson and Kondo impurity models and aims at extending his research to translationally invariant systems such as the Kondo lattice model, which is the paradigmatic model of heavy fermions. For this, he wanted to use the VUMPS method. MK approached YO to learn about the VUMPS im- plementation and succeeded in implementing his own VUMPS code. Since heavy- fermion systems have not been much studied by using tensor networks, the VUMPS calculation will be able to reveal a new aspect of the heavy fermions.

7. Tensor network application to non-Hermitian systems
   - Wei-Lin Tu (WL) has had a discussion with a PCS member, Dr. Verma, and learned about the non-Hermitian topological order in the non-reciprocal lattice. This in-

spired WL to think about a possible application to MPS or DMRG tensor network with open or twisted boundary conditions. Especially, the wave number cannot be straightforwardly defined and thus within a finite-size system how to simulate the spectral weight of a given system becomes an issue of interest. WL and Verma have now come to understand the situation in the tight-binding case but with the strong correlation, its proper construction becomes our following goal. We anticipate that a paradigm can be built for studying the bulk-edge correspondence using tensor network ansatz.

5. Outlook

We anticipate that the ASG activity will yield multiple papers. Our collaboration will persist throughout the year, and we would be delighted to revisit Daejeon in the future.

Quantum-functional mesoscopic weak links
Convener: Robert Shekhter
Co-convener: Hee Chul Park

Advanced Study Group (ASG) was active throughout the calendar year 2023, during which its activities followed the approved research plan. Collaborative efforts during three meetings on-site at PCS and abroad (in Gothenburg, Sweden) were complemented by individual work of the ASG members during the year 2023 and regular online activity. Research carried out within the ASG has resulted in a number of papers, published, submitted, or prepared for publications (refs. [1–8]). The three most significant scientific achievements, in our opinion, are the following:

1. Quantum communication between remote superconducting charge qubit states via Schrödinger cat coherent vibrational states was suggested (Refs. 1).
2. New method of testing a nanomechanically activated flying Cooper pair box – qubits was suggested (Refs. 2).
3. Magnetizing of a superconductor by spin-dependent tunneling injection of electrons was predicted (Ref. 3).

Reviews of the ASG research activity, following the directions stated in the approved Research Plan, are presented below.

A. Quantum communication by nanomechanical coherent state (Ref. 1)

Within this direction, we were focusing on theoretical studies of a network of superconducting charge qubit devices coupled to a single nanomechanical resonator. The following steps in achieving the quantum communication between qubit devices have been formulated as separate projects, listed below.

- Transduction of quantum information from charge qubit to nanomechanical cat-state
- Inter–charge-qubit transduction of the quantum information via nanomechanical cat-state

Below we present a short description of the above activities.

a) Transduction of quantum information from charge qubit to nanomechanical cat-state (Ref. 1)

In this project, we have suggested a nanoelectromechanical setup and corresponding time-protocol of its manipulation by which we transduce quantum information from charge qubit to nanomechanical cat-state. The setup is based on the AC Josephson effect between bulk superconductors and mechanically vibrating mesoscopic superconducting island in the regime of the Cooper pair box. Starting with a pure state with quantum information initially encoded into superposition of the Cooper pair box states, applying a specially tailored time-protocol upon bias voltage and gate electrodes, we obtain a new pure state with information finally encoded into superposition of nanomechanical coherent states constituting the cat-state. This performance is achieved using quantum entanglement between electrical and mechanical states. Nanomechanical cat-states serve as a "storage" of quantum information, motivated by significantly longer decoherence time with respect to the charge qubit states, from which the information can be transduced back to the charge qubit applying the reverse time protocol. For the experimental realization of this work, we have been trying to fabricate such a device that a Cooper pair box is placed in between two superconducting electrodes in proximity. We defined a nanoscale structure on a substrate of Si_3N_4/Si by using electron beam lithography. With the patterned resist as an etch mask, we etched out the Si_3N_4 and Si layers so that the cantilever structure is formed. Metallic layers of Ti, Al, and Au are deposited afterward. Finally, with the application of a focused ion beam, the Cooper pair box is defined at the end of the cantilever. The device was designed to have five electrodes around the cantilever: two for the nanomechanical oscillation of the structure, the other two for the detection of the transfer of Cooper pairs, and one for the gate voltage control. Mechanical oscillation of the nanostructure was controlled and precisely controlled at 4 K in terms of displacement. We are planning to push the temperature down to 10 mK in which we can hopefully confirm the suggested theory in a superconducting state.

b) Nanomechanical manipulation of superconducting charge-qubit quantum networks (Ref. 7)

We have suggested nanoelectromechanical setup and corresponding time-protocol for controlling parameters in order to demonstrate nanomechanical manipulation of superconducting charge-qubit quantum network. We illustrate it on an example reflecting important task for quantum information processing — transmission of quantum information between two charge-qubits facilitated by nanomechanics. The setup is based on terminals utilizing the AC Josephson effect between bias voltage-controlled bulk superconductors and mechanically vibrating mesoscopic superconducting grain in the regime of the Cooper pair box, controlled by the gate voltage. The described manipulation of quantum network is achieved by transduction of quantum information between charge-qubits and intentionally built superposition of nanomechanical coherent states constituting the cat-state. This performance is achieved using quantum entanglement between electrical and mechanical states.

B. Andreev probing of flying charge qubit states (Refs. 2,4)

This direction of the ASG activity was focused on nanomechanical assistance to quantum communication by offering a mechanically movable quantum dot as a platform for the transportation of a quantum qubit state in space. Two projects concerning the mechanical pumping of Cooper pairs and Andreev testing of flying charge qubit states are shortly reviewed below.

- Nanomechanical pumping of Cooper pairs flow by oscillating single level quantum dot.
- Andreev probing of Cooper pair box flying qubits.

a) Nanomechanical pumping of Cooper pairs flow by oscillating single level quantum dot (Ref. 4)

In this project we have considered a system consisting of a single-level quantum dot that performs mechanical periodic oscillations between spatially distant normal and superconducting electrodes, approaching them at a distance that allows the exchange of electrons through the vacuum tunnel barrier. Considering that the distance between the electrodes is much greater than the tunneling length, we show that charge pumping occurs in such a nanosystem even when the electrochemical potentials of the electrodes coincide. In this case, the direction of the electron flow is determined by the position of the quantum dot level relative to the electrochemical potential in bulk electrodes. The latter can be controlled by applying a voltage between the ground and the electrodes. It is also shown that the value of the average current is critically sensitive to the strength of the tunnel coupling between the quantum dot and the superconducting electrode, which, in turn, is controlled by the amplitude of mechanical oscillations.

b) Andreev probing of Cooper pair box flying qubits (Ref. 2)

The Coulomb blockade for tunneling of Cooper pairs between a bulk superconductor and a small superconducting dot can be removed electrostatically, which brings superconducting condensates on both conductors, corresponding to the total number of Cooper pairs differing by one, into entanglement. This is how quantum states on superconducting dot called Cooper pair box (CPB) are formed, implementing a quantum bit information carrier. Time-dependent mechanical displacement of the dot allows spatial transportation of the Cooper pair box, providing transferring of quantum information in space. In this project, we suggest that experimental observation of corresponding "flying qubit" states can be achieved by injection of electrons into CPB from the non-superconducting electrode. We show that electric current occurring due to Andreev reflection of injected electrons even without the driving voltage applied to the device is determined by the mechanical motion of Cooper pair box, and the latter can be identified through oscillatory dependence of the current on electrostatic gate potential applied to the device.

C. Spin-orbit-active superconducting weak links (Ref. 3)

Electronic spin in BCS superconductor is "frozen out" by Cooper pairing of electrons in a spin-singlet state. A natural temptation to activate electronic spin in superconducting condensate is a great motivation to consider the role of spin-active electric weak links in Josephson physics. Spin-orbit interaction and local magnetic nonhomogeneity may cause a phenomenon of spin-dependent tunneling — the effect of spin-flip assisted tunneling of electrons. In this direction line, we aimed to answer the question whether or not the phenomenon of spin-depending results in achieving a net magnetization of the superconductors. The conditions for magnetizing as well as the physics of such phenomenon have been discussed. A short overview of the research is presented below as a set of the projects considered.

a) Quantum spin fluctuations caused by spin-active superconducting proximity.

In its ground state, the BCS wave function of a homogeneous superconductor describes Cooper- paired electron states. These states are time reversed with respect to each other and are eigenstates of an operator that projects the electronic spin on a certain axis, denoted here as the z-axis, which is defined by the order parameter (pairing potential) that induces the pairing. The nature of this superconducting pairing can change significantly in spin-inhomogeneous materials such as structures with paramagnetic impurities, conductors affected by spatially inhomogeneous magnetic fields, hybrid superconducting structures comprising ferromagnetic parts, etc. Examples are the suppression of superconductivity in alloys with paramagnetic impurities, the triplet proximity effect at superconductor–ferromagnet interfaces or spin-orbit active normal– superconducting interfaces, and anomalous Josephson effects in hybrid superconducting structures. Two bulk superconductors connected by a weak link in the form of a micro-constriction is an example of a hybrid structure, where an inhomogeneity affects the superconducting properties locally on the scale of the diameter a of the constriction cross-section. The extent of the influence of the constriction depends on the relation between a and the coherence length ξ, which is the length scale of the non-locality of superconducting correlations. This is because the superconducting order-parameter at any point in space is determined self-consistently in a way that involves all electrons within the coherence length ξ around the point. If $\xi \gg a$ the order parameter close to the constriction is mostly determined by bulk electron pairs located far away, in a region where there are very few electrons that have tunneled through the constriction. This is due to the fact that the density of tunneled electrons diminishes with the distance r from the point contact as $1/r^2$ (for a three-dimensional superconductor). In this case, we are allowed to use the bulk value Δ of the homogeneous superconductor's order parameter even in the vicinity of the weak link and assume that the order parameter pairs electrons that are eigenstates of the spin operator s_z. Depending on the nature of the weak link we may have different scenarios for electron transfer between the superconductors through the constriction. Here we consider the mechanism of spin-dependent tunneling. The spin dependence may arise from, e.g., scattering off magnetic impurities or spin-orbit interactions in the weak link. Our results below do not rely on the origin of the specific spin-dependent tunneling but do depend on its symmetry. An immediate consequence of spin-dependence of the tunneling is that the eigenvalue of s_z is no longer conserved for tunneling electrons, and hence all the projections of the spin fluctuate quantum-mechanically. This opens the question of whether or not these fluctuations result in the appearance of magnetization in the BCS superconductors due to the emergence of spin-polarized Cooper pairs. The answer to this question is the scope of this paper. Although spin-dependent tunneling generates quantum spin fluctuations, we find that for an unbiased system, the formation of spin-triplet Cooper pairs is blocked by destructive interference between different quasi-electron and quasi- hole tunneling channels. More precisely, the blockade occurs if the densities of states of quasi- electron and quasi-hole excitations are the same (which is the case if the normal electron density of states is constant across the Fermi level). This blockade can, however, be lifted by applying a voltage bias that creates an electrostatically induced imbalance between the two tunneling channels.

b) Two mechanisms of spin-flip scattering caused by spin-dependent tunneling and two types of magnetic ordering.

It is easy to see that two types of spin-dependent tunneling processes for creating spin-triplet Cooper pairs are possible. The first type of tunneling involves the reflection of one of the electrons of a Cooper pair, which first tunnels from one lead to the other and then back, while flipping its spin. It gives rise to static magnetization in each of the superconducting leads, proportional to the square of the order parameter (energy gap) in that lead. Either a bias voltage or an intrinsic imbalance in the densities of states suffice for creating this static magnetization. The second type of processes is due to transmission of a Cooper pair from one superconducting lead to the other by the sequential tunneling of the two paired electrons, with one of them flipping its spin. In the presence of a bias voltage it leads to a time-dependent magnetization and an ensuing oscillatory spin current, both proportional to a product of the order parameters of the two superconductors.

c) Role of time reversal symmetry and effect of external magnetic field in magnetizing a superconductor.

Two types of magnetizations were shown to be built up by two mentioned mechanisms of the backscattering. Spin-flip reflection-induced magnetization is time-independent and is non-zero only if time reversal symmetry of the system is broken. This underlines the crucial role of the external magnetic field, which has to complement the spin-orbit interaction in order to generate a time-independent magnetization. The time-dependent part of magnetization determining the spin current in the system is induced even if time reversal symmetry is not broken and reminds the similar results for the charge Josephson supercurrent.

d) Physics of the magnetizing, induced by tunnel injection of triplet Cooper pairs.

Non-dissipative electron transport in a superconductor is a property of its single macroscopic quantum ground state (here taken to be the BCS ground state) and is, therefore, subject to various interference phenomena. A well-known example of such an interference phenomenon is the dc Josephson effect, where a non-dissipative current between two superconductors connected by a weak link is a function of the phase difference between their ground states. In this paper, we have presented a new type of quantum interference phenomenon, which governs spin-dependent tunneling through a weak link between two bulk superconducting leads. We have shown that a bias on the junction (together with such tunneling) creates spin-triplet Cooper pairs, giving rise to both a Josephson-like ac spin current and a static magnetization in the leads. While static magnetizations can appear in the absence of a bias in superconductors lacking balance between their quasi-electron and quasi-hole states, the spin current necessitates the junction to be biased. As we discuss below, the vanishing of the ac spin current in the absence of a bias voltage can be viewed as the result of destructive interference between different channels of electron tunneling. Tunneling processes, which make the spins fluctuate and create spin-triplet Cooper pairs, can be viewed as scattering events between different eigenstates of the spin operator s_z and can be treated by second-order perturbation in the tunneling Hamiltonian. We have identified two possible processes capable of creating spin-triplet Cooper pairs, one involving the transmission of a Cooper pair from one lead to the other while being converted from a spin-singlet to a spin-triplet Cooper pair. The other represents the reflection of one of the electrons of a Cooper pair, which first tunnels from one lead to the other and then in a second step tunnels back, flipping its spin going either from left to right or from right to left. Here spin-singlet Cooper pairs are converted to being spin- triplet pairs, while staying in the same lead. In the presence of a bias voltage, the transmission- type tunneling gives rise to a time-dependent magnetization and an oscillatory spin current, while the reflection-type leads to a static magnetization. The latter can occur even in an unbiased system, provided that the leads' densities of states are imbalanced, having for instance an excess of quasi- electron states as compared to the quasi-hole ones. We note that if none or both of the paired electrons flip their spin during a transmission event the transferred spin-singlet Cooper pair will contribute to the Josephson charge current, while if during the reflection event the electron does not flip its spin while tunneling back and forth, or flips it twice, no effect will be produced. In both types of tunneling, transmission and reflection, the system is in a virtual state after the first tunneling event, with one electron in an excited quasi-electron or quasi-hole state in the left lead and the other electron in an excited quasi-electron or quasi-hole state in the right lead. The total probability amplitude for spin-triplet Cooper pair formation by either transmission or reflection as described above is the sum of the probability amplitudes associated with the four channels. Since these are probability amplitudes rather than probabilities they will, in the language of quantum mechanics, interfere with each other. As seen in the expressions for the magnetization above, it vanishes when the junction is not biased and the quasi-electron and quasi-hole states in the superconductors are balanced, i.e., this interference is then destructive and no spin-triplet Cooper pairs are formed. More precisely, the (quasi-electron, quasi-hole) and (quasi-hole, quasi-electron) channel amplitudes interfere destructively as do the (quasi-electron, quasi-electron) and (quasi-hole, quasi-hole) channel amplitudes. This is the result of the electron-hole symmetry in BCS superconductors and holds for both types of tunneling, transmission and reflection. The crucial condition for the magnetization to appear is an imbalance of quasi-electron and quasi-hole states. If a voltage bias V is applied to the weak link there will be an electric field between the two superconductors that will break the balance between the effect of these states by shifting the energy of the quasi-hole and quasi-electron states by eV in opposite directions. This shift lifts the destructive interference so that the probability for spin triplet Cooper-pair formation becomes finite and allows us to view the role of the bias voltage for magnetizing the superconducting leads as a field effect on spin-dependent tunneling. The application of a bias voltage also affects the superconducting phase difference according to the Josephson relation, leading to oscillatory magnetization, which implies the existence of a spin current. We emphasize that the consequences of Cooper-pair transmission and single-electron reflection of one half of a Cooper pair for the magnetization of the superconductors are qualitatively different. The transmission of spin triplet Cooper pairs — when triggered by a bias voltage — resembles the ac Josephson charge-current carried by spin-singlet Cooper pairs. In contrast, the reflection process gives rise to a static (time- independent) magnetization, which can be triggered and tuned electrically by a dc bias voltage, but exists even in its absence. Both the predicted dc and ac magnetization effects are interesting examples of dissipation-less superconducting spintronic phenomena. The effect of spin-polarized Cooper-pair tunneling can be enhanced if one of the bulk superconductors is replaced by a small superconducting grain. In this case spin-triplet Cooper pairs injected into the grain can be accumulated over time until a stationary state is reached, where no supercurrent flows and a certain fraction of the Cooper pairs is spin-polarized. The physics would be similar to that of a superconducting magnetic alloy, where paramagnetic impurities give rise to spin-flip scattering. In our case spin-dependent tunneling plays the role of the impurity-induced spin scattering, an important difference being that the scattering is not random but well controlled and electrostatically tunable. As a result, a tunable net magnetization of the grain can be expected. In the magneticalloy case suppression of spin-singlet pairing is controlled by the parameter$(\sim /\tau s)/\Delta$, where τs is the spin-flip scattering time. In our case the role of τs is determined by the modulus of the inverse probability amplitude for an electron to tunnel and flip its spin. Finally, we note that the effect of spin-singlet and spin-triplet Cooper pairs on the superconducting charge- and spin currents are different. When it comes to the charge current only the injection of spin-singlet Cooper pairs into the ground state of a BCS superconductor can be supported. Therefore spin-triplet Cooper pairs are filtered out from contributing to superconducting charge transport. When it comes to the spin current, only spin-triplet Cooper pairs can contribute and spin-singlet Cooper pairs are filtered out. We hence observe an interesting new example of spin-charge separation.

In addition to the activity listed above, a number of formal and informal meetings, both in online and offline formats, took place during the year 2023 ASG meeting was organized as an ASG abroad meeting and was held in Gothenburg, Sweden. The report concerning this workshop meeting is attached to this annual report.

Finally, we would like to note that our work at the PCS would have been significantly less productive without the greatly appreciated support and very efficient assistance from the director of the center, Prof. Sergej Flach, the visitors program coordinator Dr. Jung-Wan Ryu, his assistants Ms. Jaehee Kwon and Ms. Gileun Lee, as well as all other staff and technical support members.

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Computational approaches to correlated systems: Applications to diverse materials
Convener: Ara Go

Outline
The activities of this ASG meeting can be summarized in two main parts. First, the ASG members collaborated on projects involving ruthenium compounds. Second, there were several discussions with guest scientists, including theorists and experimentalists. Listed below is a list of the participating scientists. Additionally, we briefly describe their activities during the ASG meeting.

- Ara Go (Chonnam National University)
- Sooran Kim (Kyungpook National University)
- Bongjae Kim (Kunsan National University)
- Hee Chul Park (PCS)
- Se Young Park (Soongsil University)
- Minjae Kim (POSTECH)
- Chang Jong Kang (Chungnam National University)
- Jaeho Han (PCS)
- Kyoo Kim (KAERI)
- Choong Hyun Kim (Seoul National University)
- Hosub Jin (UNIST)
- Hyun-Yong Lee (Korea University Sejong Campus)
- Hoyoung Jang (PAL)
- Ki Hoon Lee (Inchon National University)
- Jeongwoo Kim (Inchon National University)
- Hyeong Jun Lee (KAIST)

Collaboration on ruthenium compounds
Phase diagram of ruthenates heterostructure

In this project, employing the heterostructural unit, we discuss the role of the correlation in layered ruthenates, a prototypical 4d transition metal oxide. Layered ruthenates are a unique class of systems that manifest electronic and magnetic properties from various competing energy scales. At the heart of such features lies the multi-orbital physics, especially, the orbital-selective behaviors. We investigated $SrRuO_3$–$SrTiO_3$ heterostructure as a model system of a highly tunable platform to obtain emergent properties. Employing the DFT+DMFT approaches, we attempt to investigate the orbital-dependent physics of the system and identify the competing magnetic fluctuations.

Discussions with guest scientists
Variational Tensor Network Operator (presented by Prof. Hyun-Yong Lee)

Tensor network representation for quantum many-body wavefunction has been recognized a powerful and promising tool for studying strongly correlated systems. There exists a series of optimization algorithms that enables us to achieve a ground state of a quantum many-body Hamiltonian in the TN representation. Most of algorithms fall into two categories, namely 1) variational optimization and 2) imaginary time evolution. The celebrated DMRG is the most successful TN algorithm based on the variational principle. The DMRG is extremely powerful, but at the price of a high computational demand. On the other hand, the imaginary time evolution in the TN representation is simple in its implementation and also computationally cheap. However, it suffers inevitable errors that might be important and unmanageable depending in some cases. Here, we propose a way of optimizing the TN wavefunction, namely variational TN operator (VTNO), that takes advantage of both variational optimization and imaginary time evolution. The VTNO captures the non-trivial phases of matter such as the spontaneous symmetry breaking, symmetry protected and intrinsic topological phases. We discuss the central idea and benchmark results of VTNO for several representative models such as the transverse field Ising mode and cluster model.

Search for spin liquid in triangular lattice antiferromagnets (presented by Dr. Jaewook Kim)

Recently, realization of a disordered ground state by means of quantum fluctuation, i.e. quantum spin liquid, has attained substantial interest. While, earlier studies have focused on Kagome and/or pyrochlore systems with strong geometrical frustration, recently 2-dimensional triangular lattice spin systems, despite its simple structure, are also found to display salient features geometrically frustration down to very low temperature. In this talk, I will present several experimental examples of such cases including $TbInO_3$, $Na_2BaM(PO_4)_2$ (M = Mn, Ni, Co), and $M_2Mo_3O_8$.

X-ray scattering studies of ubiquitous charge order in superconducting cuprates (presented by Dr. Hoyoung Jang)

We review past experiments on superconducting cuprate materials focusing on the signature of charge ordering near/in the superconducting phase. We discuss theoretical suggestions to understand mechanisms beyond the ubiquitous charge order and essential terms for reliable microscopic calculations.

Deep Learning in Quantum Phase Transitions
Convener: Victor Kagalovsky

The ASG foreign members:

- Victor Kagalovsky (VK) – convener (Shamoon College of Engineering, Israel) June 11

– July 8

- Igor Yurkevich (IY) (Aston University, UK) June 13 – July 9
- Keith Slevin (KS) (Osaka University, Japan) June 19 – July 9
- Mikhail Fistul (MF) (Ruhr-Universität, Bochum, Germany) June 26 – July 9
- Tomi Ohtsuki (TO) (Sofia University, Tokyo, Japan) June 26 – July 1
- Sergey Kravchenko (SK) (Northeastern University, Boston, USA) June 23 – June 29

joined the PCS members:

- Alexei Andreanov (AA)
- Dario Rossa (DR)
- Tilen Cadez (TC)
- Anton Parafili (AP)
- Yeongjun Kim (YK)

The topics of the ASG research plan:

- topological insulators
- 1D and 2D strongly interacting frustrated spin-lattice systems
- Kitaev 2D spin-interacting model
- iron-based superconductors
- quasi-1D and 2D superconducting frustrated arrays of quantum Josephson junctions/qubits

These topics were addressed in numerous intensive discussions. Below I briefly describe the main subjects of these discussions as well as the topics of our collaborative research.

DR presented to VK and IY his study of free quantum mechanical systems, defined on random graphs with a fixed number of connections (built via the celebrated Watts-Strogatz algorithm). His preliminary numerical results suggest that these systems, once perturbed by a local and small many-body interaction term, show very different quantum many-body chaotic properties which are intimately related to the properties of the underlying graph. To better understand this surprising connection, supervised NN architectures are used. The preliminary results suggest the mean diameter of the graph is the key property controlling the quantum many-body chaotic features of the final model. Future collaboration in machine learning was discussed.

TO, KS, VK, and SK had several intensive discussions. KS and TO explained their recent work with Yosuke Harashima and Tomohiro Mano on simulations of the metal-insulator transition in doped semiconductors. In particular, how a convolutional neural network (CNN) can perform image recognition of Kohn-Sham orbitals obtained in density functional calculations in a computational model of a doped semiconductor. Results concerning the generalization ability of these CNNs were presented and discussed. TO introduced his recent work on reconstructing the Hamiltonian of a quantum dot from noisy data for magneto-conductance oscillations. TO, KS, VK, and SK discussed the possibility of using deep learning to analyse conductance noise data obtained by SK for two-dimensional electron gases.

KS, AA, and IBS colleagues discussed AA and colleagues' recent work on flat band models, thermalization in the SYK model, and the Rosenzweig-Porter (RP) model. A collaboration with TO, KS, AA, and colleagues to apply deep learning to identify various phases in the RP model was suggested.

TC, AA, and IY study the correlation property and superconductivity in the multifractal system. Particularly, they consider an ensemble of Fibonacci chains with open boundary condition. With numerical techniques, they observe the power-law dependence for the spatial correlation function which is a signature of multifractality. Such correlations can lead to an enhancement of superconductivity. Their analytical and numerical results confirm that one-dimensional Fibonacci chains show enhancement of the superconducting critical temperature, compared to the standard BCS theory.

AP studies the influence of the electron-electron interaction on the transport properties through a single-electron transistor (SET) strongly coupled to the two reservoirs via single-mode quantum point contacts. The details of the Luttinger-liquid technique applied to the problem to cover the effects of interaction were verified during the meeting with VK and IY. The considered device exhibits the properties of the two-channel charge Kondo model. The possibility of applying the considered model to the recently experimentally created (in the group of Frederic Pierre) metal-semiconductor hybrid SET formed in 2DEG and operating in the quantum Hall regime has been argued. The problem of the logarithmical correction to the electrical conductance and the definition of the Kondo temperature at the limit of tunnel barriers is formulated.

IY and VK have significantly advanced their study of a strongly interacting one-dimensional (1D) system with N channels, in particular the conditions necessary for the coexistence of various perturbations. The most general interaction (beyond forward-scattering quadratic terms in the Lagrangian) is restricted by the neutrality requirement, meaning that each term in the Hamiltonian conserves the number of particles. To become relevant and open a gap, the perturbation has to represent a new field, and new fields have to preserve the form of the Lagrangian. There is another constraint (formulated by Haldane) on the type of perturbations that are allowed to coexist.

The conductance (in e^2/h units) of the remaining free fields can be presented as the difference between the initial conductance of all N channels and the conductance eliminated by K compatible relevant perturbations which freeze K corresponding fields. The variety of possible combinations of the relevant perturbations provides the variety of possible fractional conductances.

We also had one seminar (June 28):
Keith Slevin & Tomi Ohtsuki, Osaka University & Sophia University, Japan
Analysis of KS eigenfunctions using a CNN in simulations of the MIT in doped semiconductors

On July 6 we had an informal discussion when we tried to summarize our activities. During this discussion, MF presented a short review of a theoretical study (in collaboration with AA) of macroscopic quantum phases and quantum phase transitions occurring in different solid state and optical systems, e.g., Josephson junction arrays, superconducting qubits arrays, and arrays of Rydberg atoms. In particular, he discussed generic quantum Hamiltonians allowing to establish rich phase diagrams in such systems, and the method allowing to reduce complex quantum Hamiltonians to classical Ising model in (n+1) dimensions. After that, the participants discussed how to apply the machine learning technique for the study of quantum phases and quantum phase transitions.

We believe that the results of ASG activity will result in more than one paper. We will continue our collaboration throughout the year and obviously will be very happy to repeat our visit to Daejeon.

Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links
Convener: Robert Shekhter
Co-convener: Junho Suh

Our Advanced Study Group (ASG) was active throughout the calendar years 2020–2022, during which its activities followed the approved research plan. Collaborative efforts during two meetings on site at PCS were complemented by individual work of the ASG members during the years 2020–2022 and regular online activity motivated by COVID travel restrictions. Research carried out within the ASG has resulted in a number of papers (published, submitted or prepared for publication, Refs. [1–16]). The three most significant scientific achievements, in our opinion, are the following:

1. Schrödinger CAT coherent vibrational states were shown to be generated by biased Cooper Pair Box Qubit entangled with nanomechanical resonator [12].
2. Phenomena of Spin and Charge, generated by time-dependent Rashba coupling were predicted [4, 8, 9, 10].
3. Magnetometry of the Aharonov–Casher phase in spin-orbit-active electric weak links was suggested [11].

A review of the ASG research activity, following the directions stated in the approved Research Plan, is presented below.

A. Spin- and Charge Transport through Spin-Orbit (SOI)-Active Electric Weak Links

Within this direction we were focusing on theoretical studies of spin and charge transport through spin-orbit-interaction-active (SOI-active) weak links, bridging magnetic leads. Our research was grouped within the following projects:

(a) Electric and magnetic gating of electron transport through SOI-active weak links;
(b) Spin- and charge generation driven by AC Rashba coupling;
(c) Magnetometry of Aharonov–Casher (A–C) phase.

Below we present a short description of the above activities.

(a) *Electric and magnetic gating of electron transport through SOI-active weak links [3, 10]*

A Datta–Das spin field-effect transistor is built of a heterostructure with a Rashba spin-orbit interaction (SOI) at the interface (or quantum well) separating two possibly magnetized reservoirs. The particle and spin currents between the two reservoirs are driven by chemical potentials that are (possibly) different for each spin direction. These currents are also tuned by varying the strength of the SOI, which changes the amount of the rotation of the spins of electrons crossing the heterostructure. In the paper [10] we investigate the dependence of these currents on additional Zeeman fields on the heterostructure and on variations of the reservoir magnetizations. In contrast to the particle current, the spin currents are not necessarily conserved; an additional spin polarization is injected into the reservoirs. If a reservoir has a finite (equilibrium) magnetization, then we surprisingly find that the spin current into that reservoir can only have spins which are parallel to the reservoir magnetization, independent of all the other fields. This spin current can be enhanced by increasing the magnetization of the other reservoir and can also be tuned by the SOI and the various magnetic fields. When only one reservoir is magnetized then the spin current into the other reservoir has arbitrary tunable size and direction. In particular, the spin current changes as the magnetization of the other reservoir are rotated. The optimal conditions for accumulating spin polarization on an unpolarized reservoir are to either apply a Zeeman field in addition to the SOI, or to polarize the other reservoir.

The SOI is found to generate magnetization components in each lead of the device, which rotate in the plane of the electric field (generating the SOI) and the weak link, only if the "bare" magnetization of the other reservoir has a nonzero component in that plane [3]. The SOI affects the charge current only if both reservoirs are polarized. The charge current is conserved, but the transverse rotating magnetization current is not conserved because the SOI in the weak link generates extra spin polarizations which are injected into the reservoirs.

(b) *Spin- and charge generation driven by AC Rashba coupling [4, 8, 9]*

In this project we have shown that a controllable dc magnetization is accumulated in a junction comprising a quantum dot coupled to nonmagnetic reservoirs if the junction is subjected to a time-dependent spin-orbit interaction [8]. The latter is induced by an ac electric field generated by microwave irradiation of the gated junction. The magnetization is caused by inelastic spin-flip scattering of electrons that tunnel through the junction, and depends on the polarization of the electric field: a circularly polarized field leads to the maximal effect, while there is no effect in a linearly polarized field. Furthermore, the magnetization increases as a step function (smoothed by temperature) as the microwave photon energy becomes larger than the absolute value of the difference between the single energy level on the quantum dot and the common chemical potential in the leads.

An unbiased one-dimensional weak link between two terminals, subjected to the Rashba spin-orbit interaction caused by an AC electric field which rotates periodically in the plane perpendicular to the link, is shown to inject spin-polarized electrons into the terminals [4]. The injected spin polarization has a DC component along the link and a rotating transverse component in the perpendicular plane. In the low-rotation-frequency regime, these polarization components are proportional to the frequency. The DC component of the polarization vanishes for a linearly polarized electric field.

The electric charge, generated by AC Rashba coupling was predicted in our paper [8]. An AC electric field applied to a junction comprising two spin-orbit coupled weak links connecting a quantum dot to two electronic terminals was proposed to induce a DC electric current and to generate a voltage drop over the junction if it is a part of an open circuit. This photovoltaic effect requires a junction in which mirror reflection symmetry is broken. Its origin lies in the different ways inelastic processes modify the reflection of electrons from the junction back into the two terminals, which leads to uncompensated DC transport. The effect can be detected by measuring the voltage drop that is built up due to that DC current. This voltage is an even function of the frequency of the AC electric field.

(c) *Magnetometry of Aharonov–Casher (A–C) phase [11]*

The spin-orbit interaction (SOI) is a key tool for manipulating and functionalizing spin-dependent electron transport [11]. The desired function often depends on the SOI-generated phase that is accumulated by the wave function of an electron as it passes through the device. This phase, known as the Aharonov–Casher phase, therefore depends on both the device geometry and the SOI strength. In this project we proposed a method for directly measuring the Aharonov–Casher phase generated in an SOI-active weak link, based on the Aharonov–Casher-phase dependent anisotropy of its magnetoconductance. Specifically, we consider weak links in which the Rashba interaction is caused by an external electric field, but our method is expected to apply also for other forms of the spin-orbit coupling. Measuring this magnetoconductance anisotropy thus allows calibrating Rashba spintronic devices by an external electric field that tunes the spin-orbit interaction and hence the Aharonov–Casher phase.

B. Superconducting Nanomechanics

Our research along this direction was a very active one and significant progress was achieved in understanding of quantum dynamics of voltage driven nanoelectromechanical Cooper Pair Box. Theoretical effort during reported period was accompanied with progress in experimental assembling nanoelelectromechanical (NEM) shuttle devices. Mutual work experimentalist and theoreticians resulted in of common publication were the main result- the prediction of nanomechanical coherent CAT states – was presented.

The following projects were in focus of our research:

(a) Nanomechanical phenomena driven by quantum force originated from hybridization of Cooper pairs between two superconductors forming a Josephson junction was formulated and studied for different experimental set's up;
(b) Quantum nano-vibrations entangled with superconducting Cooper pair box were studied;
(c) Nanomechanics driven by Cooper pair flow was formulated and studied.

Below we present a short description of the above activities.

(a) *Superconducting nanomechanics, driven by Josephson force [13, 14, 15]*

In a number of our recent works, a new concept of Josephson force has been introduced. Usually, the force acting on the moving shuttle is associated with the localization of the charge or spin on it. At the same time, the incorporation of the superconducting elements into device brings into the scene a fundamentally new type of force which has an entirely quantum origin. Namely, this force, which we called the Josephson force, is associated with the positional dependence of the amplitude of the exchange of Cooper pairs between the superconductor and the moving subsystem, on the one hand, and the quantum superposition of different states of Cooper pairs, on the other. In particular, if the system is in a ground state this force is determined by the derivative of the Josephson energy regarding the distance between the moving part and the superconductor. For example, for the movable Cooper pair box positioned between two superconductors the direction and strength of this force are controlled by Cooper pair energy and the phase difference between superconducting leads.

(b) *Quantum Nano-vibrations Entangled with Superconducting Cooper-Pair Box [12]*

The possibility of coherent quantum nano-mechanical encoding of superconducting charge qubit states was demonstrated by us recently [12]. Such encoding was proven to appear as a superposition of vibrational coherent states entangled with Qubit Cooper-pair states in a movable box (a vibrational "Schrödinger cat state") being achieved by DC biasing the device. In particular, it was demonstrated, that at special bias voltages, when the frequency of Josephson phase oscillations coincides with the frequency of the mechanical vibrations, the initial pure quantum state of the device (its ground state) develops into one described by the entanglement of qubit states with two coherent mechanical vibrational states with opposite vibrational phases and amplitudes linearly growing in time. The performed research was focused on analyzing the possibility to control such states by bias voltage manipulations. We have calculated the entropy of entanglement for a NEM single-electron transistor (NEM-SET device) with quantum nanomechanical vibrations and have shown that this entropy monotonically increases with time (after the bias voltage is switched on) from the value equal to zero to its maximum value (equal to log 2). This increase is accompanied by a growth with time of the rectified Josephson current through the device. It was also shown that a sudden reversal of the polarity of the voltage bias induces a monotonical decrease in time of the DC Josephson current, following the monotonical decrease of the entanglement entropy. The possibility to generate four vibrational coherent states entangled with Cooper-pair box states was demonstrated if a certain protocol of bias voltage variations is chosen. We have performed a “Wigner tomography” of the predicted quantum nano-vibrational states and have demonstrated its negative values in certain domains of the coordinate-momentum space (see Fig. 1).

(c) *Nanomechanics driven by Cooper pair flow [13, 14, 15]*

The potential performance of the Josephson force can be illustrated by considering the nanomechanical weak link composed of a carbon nanotube suspended above a trench in a normal metal electrode and positioned in a gap between two superconducting leads. The nanotube is treated as a movable single-level quantum dot (QD) in which the position-dependent superconducting order parameter is induced as a result of Cooper pair tunneling.

We have shown that in such a system, the Josephson force may result in the generation of self-sustained bending vibrations if a bias voltage is applied between normal and superconducting electrodes [14]. The appearance of such oscillation is controlled by the position of the QD energy level and the direction of the bias voltage. We have also shown that the self-sustained mechanical vibrations strongly affect the DC current through the system, leading to transistor and diode effects. The latter can be used for the direct experimental observation of the predicted phenomena. We also demonstrated that a similar phenomenon may be induced by an electrostatic force [7].

We have employed the phenomena considered above, to investigate the influence of the flow of Cooper pairs through Andreev nanomechanical weak links on the quantum dynamics of a mechanical subsystem. We found that the Cooper pair flow generated by the bias voltage gives rise to pumping or cooling of the mechanical subsystem depending on the direction of the electronic flow [13, 15]. It also has been demonstrated that the transition between these two regimes is controlled by the strength of the tunnel coupling between the nanotube and superconducting STM tip and the relative position of the electronic level. To study these regimes, we used a Wigner function approach to characterize the state of the mechanical subsystem. The amplitude of the self-sustained oscillations in the pumping regime was analyzed numerically, while the effective temperature of the mechanical subsystem in the cooling regime was obtained analytically.

C. Nanomechanics Driven by Spin-Polarized Electrons

Magnetic exchange force comes into nanomechanical interplay if nanomechanical shuttle device is made of magnetic material. In contrast to electric shuttle device where mechanical deformations are induced by electric charge accumulated by electrons at the shuttle, here the accumulated electronic spin determines “spintro-mechanical” performance of the device. Therefore, there is no need to electrically bias the device to get electronic pumping of the nano-vibrations and one can consider other non-electric transport phenomena such as, e.g., thermal heat transport as a driver of nanomechanical vibrations. Number of projects were considered along that direction which are listed below:

(a) Thermal breakdown caused by spintro-mechanic shuttling;
(b) Coulomb promotion of the spintro-mechanical shuttle vibrations;
(c) Polaronic suppression of shuttle spintro-mechanics.

Below we present a short description of the above activities.

(a) *Thermal breakdown caused by spintro-mechanic shuttling [2]*

A thermally driven single-electron transistor with magnetic leads and a movable central island (a quantum dot) subject to an external magnetic field was considered within this project. The possibility of a mechanical instability caused by magnetic exchange interactions between spin-polarized electrons in this system was studied by the density matrix method. We proved analytically that for noninteracting electrons in the dot there is no such mechanical instability. However, for finite strengths of the Coulomb correlations in the dot we numerically found critical magnetic fields separating regimes of mechanical instability and electron shuttling on the one hand and damped mechanical oscillations on the other. It was shown that thermally induced magnetic shuttling of spin-polarized electrons is a threshold phenomenon, and the dependence of the threshold bias temperature on model parameters was calculated.

(b) *Coulomb promotion of the spintro-mechanical shuttle vibrations [1]*

Exchange forces on the movable dot ("shuttle") in a magnetic shuttle device depend on the parity of the number of shuttling electrons. The performance of such a device can therefore be tuned by changing the strength U of Coulomb correlations to block or unblock parity fluctuations. We show that by increasing U the spintromechanics of the device crosses over, at $U = U_c(T)$, from a mechanically stable regime to a regime of spin-induced shuttle instabilities (neglecting electric forces). This is due to enhanced spin-dependent mechanical forces as parity fluctuations are reduced by a Coulomb blockade of tunneling and demonstrates that single-electron manipulation of single-spin controlled nanomechanics is possible.

(c) *Polaronic suppression of shuttle spintro-mechanics [6]*

Current–voltage characteristics of a spintro-mechanical device, in which spin-polarized electrons tunnel between magnetic leads with anti-parallel magnetization through a single-level movable quantum dot, was calculated in this project. New exchange- and electromechanical coupling-induced (spin-polaronic) effects that determine strongly nonlinear current–voltage characteristics were found. In the low-voltage regime of electron transport the voltage-dependent and exchange field-induced displacement of the quantum dot towards the source electrode leads to a nonmonotonic behavior of the differential conductance, which demonstrates the lifting of spin-polaronic effects by an electric field. At high voltages the onset of electron shuttling results in a drop of the current and a negative differential conductance, caused by a mechanically induced increase of the tunnel resistances and an exchange field-induced suppression of spin-flips caused by an external magnetic field. The dependence of these predicted spin effects on the oscillation frequency of the dot and the strength of electron–electron correlations is discussed.

A re-entrant behavior of electron shuttling was shown [16] to occur in a nanoelectromechanical transistor made of magnetic material where spin-polarized electrons are injected into a quantum dot with a single electron level split into two by an external magnetic field. A suppression of shuttle vibrations occurs at a certain value of a bias voltage that starts to allow for transport also through the upper energy level of the dot, while for a further increase of the voltage shuttling recovers. The effect is due to a time-dependent polaronic shift of the dot energy level, which results in a reduction of the supply of the electric power to the mechanical motion.

In addition to activity listed above a number of formal and informal meetings both in online and offline formats took place during the years 2020–2022.

Finally, we would like to note that our work at the PCS would have been significantly less productive without the greatly appreciated support and very efficient assistance from the director of the center, Prof. Sergej Flach, the visitors program coordinator Dr. Jung-

Wan Ryu, his assistants Ms. Jaehee Kwon and Ms. Gileun Lee, as well as all other staff and technical support members.

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List of ASG activities

19 January 2022 (WED)
Participants: Robert, Leonid Gorelik, Danko Radic, Sang-Jun Choi, Junho Suh, and Hee Chul Park;
"Nanomechanical cat states generated by a dc voltage-driven Cooper pair box qubit"

20 January 2022 (WED)
Participants: Robert, Leonid Gorelik, Anton Parafilo, and Hee Chul Park;
"Charge qubit entanglement enhanced by vibrational mechanics"

25 July 2022 (MON)
Participants: Robert Shekhter and Hee Chul Park;
"Quantum nanovibrations entangled with voltage biased Cooper pair box" by Hee Chul Park.

27 July 2022 (WED)
Participants: Robert, Leonid Gorelik, Danko Radic, and Hee Chul Park;
"Quantum pumping by mechanical driving" and "Moving qubit to long distance by Cat states" by Leonid Gorelik.

11 August 2022 (THU)
Participants: Chulki Kim, Junho Suh, Robert Shekhter, Leonid Gorelik, Danko Radic, Olha Bahrova, Anton Parafilo, Chang-Hwan Yi, and Hee Chul Park;
"Progress of experimental works during COVID-19 era" by Chulki Kim.

25 August 2022 (THU)
Participants: Robert Shekhter, Leonid Gorelik, Olha Bahrova, Anton Parafilo, Jae-Ho Han, and Hee Chul Park;
"Progress of experimental works during COVID-19 era" by Olha Bahrova.

01 September 2022 (THU)
Participants: Chulki Kim, Kyung-Min Kim, Sunghun Park, Robert Shekhter, Leonid Gorelik, and Hee Chul Park;
Contents: We had an ASG meeting for Nanomechanical charge pumping connected normal metal and superconducting lead, and detecting magnetization on twisted 2D magnets using diamond NV center. Leonid presented the idea of the superconducting system for pumping the entangled states between a normal lead and a superconducting lead. Chulki presented how to measure the magnetic field using a diamond NV center.

25 August 2022 (THU)
Participants: Robert Shekhter, Leonid Gorelik, Mats Jonson, Amnon Aharony, Ora Entin-Wohlman, Olha Bahrova, Anton Parafilo, Jae-Ho Han, Sunghun Park, and Hee Chul Park;
"Microwave spectroscopy of Josephson junction weak link with spin-orbit coupling" by Sunghun Park.

Members:

Formal members
Robert Shekhter (Gothenburg Univ.)
Mats Jonson (Gothenburg Univ.)
Ilya Krive (Institute for Low Temperature Physics and Engineering, Ukraine)
Amnon Aharony (Tel Aviv University)

Ora Entin-Wohlman (Tel Aviv University)
Danko Radic (Univ. of Zagreb)
Loenid Gorelik (Chalmers Univ.)
Chulki Kim (KIST)
Junho Suh (KRISS)
Hee Chul Park (IBS-PCS)

Associate members
Sang-Jun Choi (Wurzbug Univ.)
Donggeun Lee (KIST)
Olya Ilinskaya (ILTPE, Ukraine)
Olha Barohva (ILTPE, Ukraine)
Anton Parafilo (IBS-PCS)
Chang-Hwan Yi (IBS-PCS)
Sunghun Park (IBS-PCS)
Jae-Ho Han (IBS-PCS)
Nojoon Myoung (Chosun Univ.)
Sejoong Kim (UST)

3.1.6 Lectures, Colloquia, Symposia and Seminars at the Center

Date	Title	Speaker
25.09.2025	Exceptional Physics in topological systems	D. Chowdhury, India
23.09.2025	Nanomechanical cat-states in NEM-based quantum signal processing	D. Radić, Croatia
11.09.2025	Dual holography from a non-perturbative generalization of the Wilsonian RG framework	K. S. Kim, Korea
06.08.2025	Liquid O: Radiation Detection Beyond Transparency	C. Anatael, France
29.07.2025	Periodically driven systems: a versatile toolbox for quantum simulation	M. Bukov, Germany
17.07.2025	Odd-frequency superfluidity from a particle-number-conserving perspective	J. Brand, New Zealand
17.07.2025	Extreme(s) Matter – Alien Melting Behaviour of Noble Gases	E. Pahl, New Zealand
16.07.2025	Electronic structure studies of low-dimensional nanomaterials	Y. W. Choi, Korea
16.06.2025	Mysteries of Cosmic Rays: Recent Discoveries and Future Prospect	E.-S. Seo, USA
10.06.2025	Thermoelectric transport across a tunnel contact between two charge Kondo circuits	N. T. K. Thanh, Vietnam
05.06.2025	Using and analyzing quantum computation: material phase classification and entropy dynamics	T. Ohtsuki, Japan

04.06.2025	Emergent physics from nuclear lattice simulations	D. Lee, USA
27.05.2025	Topological characterisation of magnetostatic surface spin waves	K. Yamamoto, Japan
22.05.2025	Towards ultracold MgF molecules for quantum information science	E. Chae, Korea
20.05.2025	Exotic magnonic transport in 2D magnets	S. Kwon Kim, Korea
29.04.2025	Polariton quantum fluids: from out of equilibrium phase transitions to analogue black holes	A. Bramati, France
22.04.2025	Fractional conductances: S-matrix vs. Kubo formalism	V. Kagalovsky, Israel & I. Yurkevich, UK
10.04.1024	Exploring electron correlations in the breathing kagome metal Fe3Sn	S. Sharma, Poland
08.04.2025	p-atic order parameters in the fractional quantum Hall effect from non-relativistic higher-spin fields	P. Salgado-Rebolledo, Korea
03.04.2025	Quantum thermodynamics and spin transport of open one-dimensional single-band Fermi-Hubbard systems	V. P. Villegas, Philippines
27.03.2025	Effects of correlations in disorder on localization and ergodicity breaking in long-range systems	I. Khaymovich, Sweden
25.02.2025	Classical and Quantum Nonequilibrium Dynamics of Nonlinear Nanomechanical Systems	R. Lifshitz, Israel
23.01.2025	Master stability curves for traveling waves	A. Giraldo, Korea
19.12.2024	Quantifying quantum resources using the nonclassical values of Kirkwood Dirac quasiprobability and strange weak value	A. Budiyono, Indonesia
12.12.2024	Spin dynamics of coupled Ti spins on ultrathin MgO layers probed by ESR-STM	V. Sheina, Korea
10.12.2024	The Ising dual-reflection interface: Z4 symmetry, Majorana strong zero modes and SPT phases	S. Moroz, Sweden
03.12.2024	Symmetry-Protected Topological phases and Duality	M. Oshikawa, Japan
28.11.2024	Chaos Computing Using Spintronics	G. Park, Korea
27.11.2024	Localization in Flatbands: Disorder and Impurities	Y. Kim, PCS IBS
30.10.2024	The Leverage of Nuclei in the Cosmos	M. S. Smith, USA
29.10.2024	Nanomechanical two-dimensional cat states generated by a dc voltage-driven Cooper pair box	L. Gorelik, Sweden

24.10.2024	Are we on the way to the room temperature superconductivity?	B. Altshuler, USA
22.10.2024	A study of neutron star property based on the PDM-NJL crossover model	M. Harada, Japan
17.10.2024	Irreversibility & Inference: Classical & Quantum Reverse Processes via Bayesian Inversion	C. C. Aw, Singapore
15.10.2024	Shuttling of flying qubits	S. Park, PCS IBS
24.09.2024	Unification of observational entropy with maximum entropy principles	J. Schindler, Spain
03.09.2024	Probing dark energy and inflation using DESI	H.-J. Seo, USA
29.08.2024	Generalized loop braiding statistics in 3+1d topological phases: the case of twisted lattice gauge theory	J. C. Huxford, Canada
22.08.2024	Exact projected entangled pair ground states with topological Euler invariant	T. Wahl, UK
21.08.2024	Emergence of flat bands and ferromagnetic fluctuations via orbital-selective electron correlations in Mn-based kagome metal	H.-S. Kim, Korea
13.08.2024	Engineering on-demand band structures and non-Hermitian state of light in photonic crystal	H. S. Nguyen, France
27.06.2024	Experimental works on localized vibrations in nonlinear lattices	M. Kimura, Japan
25.06.2024	Josephson current signatures of Majorana Fermions in Topological insulator Josephson junction	H. Kim, PCS IBS
18.06.2024	Driven - dissipative dynamics of trapped ultracold atom systems interacting with background BECs	R. C. F. Caballar, Philippines
11.06.2024	Dirac fermion optics and electron dynamics in anisotropic bilayer graphene billiards	M. Hentschel, Germany
16.05.2024	Quantum Scaling for the Metal-Insulator Transition in a Two-Dimensional Electron System	V. Kagalovsky, Israel
07.05.2024	Josephson tunneling controlled by spin-orbit interaction	R. Shekhter, Sweden
02.05.2024	Finding the Missed Topological Operators in Lattice Models	J.-Y. Chen, China
30.04.2024	Phenomenology of Unexpected Thermal (Hall) Transports	J.-Y. Chen, China
23.04.2024	Nonlinear Energy and Charge Transport in Silicates. Experiments and semiclassical models	J. F. R. Archilla, Spain

18.04.2024	Unraveling Opinion Dynamics: Insights from Network Science and the Ising Model	Z. Akbar, Indonesia
16.04.2024	Thermoelectric transport driven by Spin-orbit coupling	D. Chowdhury, India
11.04.2024	Effects of electron wave function in optoelectronics and transport	E. H. Hasdeo, Luxembourg
04.04.2024	Absence of breakdown of ferrodark solitons exhibiting snake instability	X. Yu, China
21.03.2024	Topological phases and optimal control in the arrays of superconducting qubits	M. Gorlach, Russia
22.02.2024	From waves to chaotic flows in the cytoplasm	L. Koehler, Germany
08.02.2024	Coulomb blockade in a non-thermalised quantum dot	R. Davies, UK
30.01.2024	Exploring Light-Induced Phenomena in Condensed Matter Physics within the Framework of Density-Functional Theory	B. Kim, Korea
25.01.2024	Resonant fractional conductance in 1D Wigner chains	R. Davies, UK
04.01.2024	Correlated order at the tipping point in the kagome metal CsV3Sb5	G. Wagner, Switzerland
14.12.2023	Superconducting qubits for large-scale quantum computers - Status of development in Korea and global trend	Y.-H. LEE, Korea
30.11.2023	Measuring entanglement at finite temperatures	C. Han, Israel
29.11.2023	Introduction into the complex Ginzburg-Landau equation. Part 2	I. Aronson, USA
28.11.2023	Quantum Phase Transitions and Dynamics in Perturbed Flatbands	S. Lee, PCS IBS
27.11.2023	Introduction into the complex Ginzburg-Landau equation. Part 1	I. Aronson, USA
23.11.2023	Hierarchical Organization of Communicating Active Smarms	I. Aronson, USA
09.11.2023	Wolfram Technology for LLMs	F. Pasha, USA
03.11.2023	Unifying the Anderson Transitions in Hermitian and Non-Hermitian Systems	T. Ohtsuki, Japan
02.11.2023	Attosecond science and the Nobel prize in physics in 2023	T. T. Luu, China
01.11.2023	A Stochastic Method to Compute the L2 Localisation Landscape	K. Slevin, Japan
31.10.2023	Analytical approaches for disordered Bose-Hubbard model at fixed filling	M. Gupta, India

30.10.2023	Quasiparticle interference of Gapped Dirac cones in thin film topological insulator	A. Akbari, Germany
24.10.2023	Towards a more feasible implementation of quantum networks	N. L. Piparo, Japan
19.10.2023	What Is the Next Milestone for High-Energy Particle Colliders?	M. Peskin, USA
17.10.2023	Transport regimes for exciton-polaritons in disordered microcavities	A. Osipov, Russia
10.10.2023	Controlling Quantum Computers for Computational Advantage	A. B. Özgüler, USA
05.10.2023	Magnetizing a BCS superconductor by spin-dependent tunneling	M. Jonson, Sweden
26.09.2023	Nanomechanical control of superconducting charge-qubit networks	D. Radić, Croatia
19.09.2023	Spin-boson model for nonlinear optical conductivity of graphene	S. Dattagupta, India
12.09.2023	Polaritons in emerging materials: from fundamentals to recent developments	S. Höfling, Germany
07.09.2023	Constructing the 3D analytical response of the metallic half-space to an external charge	T. Bednarek, Poland
05.09.2023	Multipole higher-order topology and flat bands in a multimode lattice	M. Gorlach, Russia
29.08.2023	No-signaling nonlinear thermodynamic consistent models of open quantum dynamics	R. K. Ray, India
28.08.2023	Janh-Teller polaron in the spin-orbit multipolar magnetic oxide Ba2NaOsO6	L. Celiberti, Austria
10.08.2023	Quantum thermal machines in coupled spin systems: The role of anisotropic interaction	C. Purkait, India
08.08.2023	Many-body localization in Wannier-Stark ladders with long-range interactions	A. Sotnikov, Ukraine
01.08.2023	Superconducting Nanostrip Detectors for Dark-Matter Search	K. K. Berggren, USA
20.07.2023	Klein bottle partition function and tensor networks	H.-H. Tu, Germany
20.07.2023	Machine Learning in Particle and String Theory	A. Lukas, UK
19.07.2023	Chaos and Relaxation in a Dissipative Sachdev-Ye-Kitaev Model	J. Verbaarschot, USA
18.07.2023	Variational Quantum Algorithms for the Geometric Measure of Entanglement	L. Zambrano, Spain
14.07.2023	Fine-grained complexities in parameterized quantum circuits	C.-Y. Park, Canada

13.07.2023	Quantum-classical entangled approach with tensor networks for spin liquid	T. Okubo, Japan
27.06.2023	Principles of self-assembly for particles with simple geometries and complex interactions	L. Koehler, France
26.06.2023	Floquet engineering: exploring control and phenomena of high-frequency electromagnetic fields in condensed-matter structures	U. Kumar, Korea
22.06.2023	Gravity and cosmology beyond general relativity	S. Mukohyama, Japan
20.06.2023	Extraction of ergotropy: free energy bound and application to open cycle engines	T. Biswas, Poland
15.06.2023	Measuring exotic entropy in the mesoscopic systems	C. Han, Israel
13.06.2023	Superconductivity from repulsive interactions in Bernal bilayer	G. Wagner, Switzerland
12.06.2023	Strongly interacting impurities in a dilute Bose condensate	N. Yegovtsev, USA
08.06.2023	QML for optimization via variational algorithms and coordinate transformations	P. Bermejo, Spain
01.06.2023	Light matter interaction in 2D materials in weak and strong coupling regime	D. Ko, PCS IBS
31.05.2023	Role of magneto-crystalline anisotropies in complex rare-earth systems	B. Tomasello, UK
30.05.2023	Acoustoelectric transport and optical response in fluctuating regime in 2D materials	K. Sonowal, PCS IBS
25.05.2023	Internal clock for many-body delocalization	S. Bera, India
23.05.2023	Resource Saving via Ensemble Techniques for Quantum Neural Networks	M. Incudini, Italy
18.05.2023	Chaos and Krylov complexity	Z.-Y. Xian, Germany
17.05.2023	Fractional conductance in one dimension	I. Yurkevich, UK
16.05.2023	Mechanically assisted Andreev reflection	L. Gorelik, Sweden
11.05.2023	Is nature natural?	H. D. Kim, Korea
09.05.2023	Chiral induced spin selectivity and time-reversal symmetry breaking	A. Aharony, Israel
04.05.2023	Explorations of Dissipative Quantum Chaos from Non-Hermitian Random Matrix Theory	J. Kudler-Flam, USA
27.04.2023	How strong can the electron-phonon interaction in metals be?	B. Altshuler, USA
13.04.2023	Anomalous Skin Effects in Disordered Systems with a Single non-Hermitian Impurity	P. Molignini, Sweden
06.04.2023	Slowing down microwave photons with superconducting qubits	A. Ustinov, Germany

05.04.2023	Coherent tunneling of Josephson vortices	A. Ustinov, Germany
04.04.2023	Extending quantum operations of fixed-frequency superconducting qubits	Y. Kim, Korea
28.03.2023	Critical State Generators from Perturbed Flatbands: Critical-to-Insulator Transitions and Fractality Edges	S. Lee, PCS IBS
28.03.2023	Flat Band Induced Metal-Insulator Transitions for Weak Magnetic Flux and Spin-Orbit Disorder	Y. Kim, PCS IBS
23.03.2023	Adiabatic eigenstate deformations and weak integrability breaking of Heisenberg chain	D. Kurlov, Switzerland
21.03.2023	The morphological analysis of the collagen straightness in the colon mucosa away from the cancer	M. Ćosić, Serbia
14.03.2023	The complexity of Bohmian positron dynamics inside a chiral carbon nanotube	M. Ćosić, Serbia
07.03.2023	The quantum carpets in a leaky-box: Poincare's recurrences in the continuous spectrum	M. Ćosić, Serbia
22.02.2023	Gate-voltage-driven quantum phase transition in quantum point contacts	J. Hong, Korea
21.02.2023	Physical limits of non-Hermitian and non-reciprocal devices	H. Schomerus, UK
15.02.2023	Ab initio DMFT methodologies for correlated quantum materials	S. Choi, Korea
15.02.2023	DMFT+NRG: From models to real materials, from local to nonlocal correlations	S.-S. Lee, Korea
14.02.2023	Charging a quantum battery in a non-Markovian environment: a collisional model approach	D. Morrone, Italy
09.02.2023	Reinforcement learning optimization of the charging of a Dicke quantum battery	G. M. Andolina, Spain
08.02.2023	Fast and slow quantum first hitting times for target search	E. Barkai, Israel
07.02.2023	Fractional conductances in the strongly interacting 1D system	V. Kagalovsky, Israel
26.01.2023	Neural Quantum States approach to the study of volume law ground states	G. Passetti, Germany
17.01.2023	Global phase diagram of charge neutral graphene in the quantum Hall regime for generic interactions	S. J. De, India
06.01.2023	Nonlinear spectroscopy of spin chains	G. Sim, Germany
23.12.2022	Spin-1 Magnets - A u(3) Formalism	K. Remund, Japan

05.12.2022	Critical Site Percolation on the Triangular Lattice	P. Pearce, Australia
01.12.2022	Sequences of magnetic field-induced phase transitions in frustrated helimagnets of low symmetry	O. Utesov, Russia
18.11.2022	Quantum Integrability	E. Yuzbashyan, USA
17.11.2022	Exploring Long Range Dipolar Interactions: From collective dipolar spin dynamics and layer exchange to light-mediated interactions and Pauli-Blocking	T. Bilitewski, USA
15.11.2022	Observational entropic study of Anderson localization	R. Modak, India
03.11.2022	How strong can the electron-phonon interaction in metals be?	E. Yuzbashyan, USA
01.11.2022	Single-Shot Determination of Quantum Phases via Continuous Measurements	A. Patra, Denmark
27.10.2022	Many-body Localization in Disordered 1D Hubbard Model with Infinite Onsite Repulsion	B. Altshuler, USA
18.10.2022	Quantum chaotic dynamics and Krylov complexity	B. Bhattacharjee, India
13.10.2022	Master equation approach to conductivity problem or solid-state physics without Green's functions	A. Kolovsky, Russia
11.10.2022	Ferrodark solitons in a spin-1 Bose-Einstein condensate	X.-Q. Yu, China
06.10.2022	Tensor networks for classical and quantum machine learning tasks	D. Poletti, Singapore
27.09.2022	Quantum network tomography using Rydberg gases	K. Mukherjee, India
13.09.2022	Noise-assisted quantum transport and mobility-edges	D. Dwiputra, Indonesia
30.08.2022	Universal principles of moiré band structures	J. Park, Germany
25.08.2022	Quantum Thermometers, Quantum Batteries, and lesser demons	S. Nimmrichter, Germany
23.08.2022	Variational Tensor Network Operator	Y.-J. Kao, Taiwan
11.08.2022	Phenomenology of the Prethermal Many-Body Localized Regime	D. Long, USA
09.08.2022	Aharonov-Bohm cages, flat bands, and gap labeling in hyperbolic tilings	R. Mosseri, France
04.08.2022	A Variational Ansatz for the Ground State of the Quantum Sherrington-Kirkpatrick Model	P. Schindler, Germany

02.08.2022	Active systems. A blind spot in physics	R. Alicki, Poland
28.07.2022	Carrier-driven ultrafast coherent phonon generation in monolayer MoSe2 explored by ab initio approach	S. Bae, Japan
26.07.2022	Nanofluidics: fluid properties at molecular scale and application to water treatment and energy conversion	A. Siria, France
21.07.2022	Equilibrium quantum batteries	F. Barra, Chile
07.07.2022	Circular Rosenzweig-Porter random matrix ensemble	W. Buijsman, Israel
05.07.2022	Flat bands and band touching in hyperbolic lattices	J. Maciejko, Canada
29.06.2022	Edge States, Solitons & Novel Phases of Topological Superfluids	J. Sauls, USA
28.06.2022	Thermalization of isolated harmonic networks under conservative noise	S. Lepri, Italy
28.06.2022	Analysis of KS eigenfunctions using a CNN in simulations of the MIT in doped semiconductors	Keith Slevin & T. Ohtsuki, Japan
23.06.2022	Semiclassical propagation: past, present and future	G. Lando, France
22.06.2022	Giant photovoltaic effect induced by wall-to-wall shift currents in semiconducting WS2 nanotubes	J. Kim, Korea
21.06.2022	Conductance cross-over for 1D wires in symmetry class BDI	F. Burnell, USA
14.06.2022	An Exact Map Between the TBG (and multilayers) and Topological Heavy Fermions	A. Bernevig, USA
09.06.2022	Coexistence of localization and transport in many-body two-dimensional Aubry-André models	C. Castelnovo, UK
09.06.2022	Catalysis in Action via Elementary Thermal Operations	J. Son, Singapore
07.06.2022	Thermalization of Classical Weakly Nonintegrable Many-Body Systems	M. Malishava, PCS IBS
07.06.2022	Thermodynamics of Quantum Synchronization	M. T. Murtadho, PCS IBS
31.05.2022	Physical and mathematical relations between quantum metric and topology of Chern insulators	T. Ozawa, Japan
26.05.2022	Floquet Weyl semimetal phases and their topological characterization	M. Umer, Singapore

26.05.2022	Mesoscopic photonic transport in open quantum systems	J. Han, PCS IBS
25.05.2022	QCD Axion Dark Matter in Reach of Nucleon Electric Dipole Moment Experiments	A. Ringwald, Germany
24.05.2022	Discrete and continuous dissipative time crystals in an atom-cavity system	A. Hemmerich, Germany
19.05.2022	Multiple Gravitons and spectral sum rules in Fractional Quantum Hall systems	D. X. Nguyen, USA
18.05.2022	Realization of Fractonic Quantum Phases in Frustrated Magnets	Y. B. Kim, Canada
17.05.2022	Classical physics and blackbody radiation	G. Benenti, Italy
12.05.2022	Invertible field transformations with derivatives	M. Yamaguchi, Japan
03.05.2022	The usefulness of quantum concepts in soft matter: quasiparticles, flat bands, and exotic topology in hydrodynamic matter	T. Tlusty, Korea
28.04.2022	Optically trapped exciton-polariton condensates	A. Nalitov, UK
26.04.2022	Scalable approach to many-body localization via quantum data	A. Gresch, Germany
19.04.2022	Robust D-Wave Superconductivity of Doped Mott Insulators	D. Sheng, USA
14.04.2022	Two-Dimensional Quantum Fluids in GaAs-Based Semiconductors	H. Choi, Korea
07.04.2022	Thermodynamics of Quantum Synchronization	M. T. Murtadho, PCS IBS
07.04.2022	Polariton condensate & valleytronics	D. Ko, PCS IBS
05.04.2022	Topological phases and flat bands of quantized light	D. Wang, China
31.03.2022	Bilayer phononic and photonic graphene: A new playground for twistronics	Y. Jing, USA
29.03.2022	Topological aspects of a multi-partite non-Hermitian Su-Schrieffer-Heeger model	R. Nehra, India
24.03.2022	Quantum computer and quantum technology	Y. Chong, Korea
22.03.2022	Kekule spin-orbit dimer phase and triplon dynamics	G. Sim, Germany
17.03.2022	Ultra-deep optical cooling of nuclear spins in semiconductor structures	K. Kavokin, Russia
10.03.2022	Orbital-selective Mott phase and non-Fermi liquid state in FePS3	M. Kim, Korea

08.03.2022	Thermodynamics of quasi-probability distributions for open quantum harmonic oscillators	J.-M. Park, Korea
03.03.2022	Avalanches and many-body resonances in many-body localized systems	A. Morningstar, USA
24.02.2022	Understanding quantum chaos through adiabatic transformations	A. Polkovnikov, USA
22.02.2022	Prethermal Phases of Matter	J. Knolle, Germany
17.02.2022	Spin-orbit splitting of Andreev states in Josephson weak links	S. Park, Spain
15.02.2022	Many-body localization and topological order in disordered interacting Ising-Majorana chains	N. Laflorencie, France
10.02.2022	Surprises in high-temperature transport	S. Gopalakrishnan, USA
08.02.2022	Neural quantum state of the long-range antiferromagnetic Ising chain	D.-H. Kim, Korea
03.02.2022	Sub-diffusive Thouless time scaling in the Anderson model on random regular graphs	L. Colmenarez, Germany
18.01.2022	Krylov complexity of many-body localization: Operator localization in the Krylov basis	C.-J. Lin, Canada
13.01.2022	Entanglement and decoherence of a system of Rydberg atoms and Bose-Einstein Condensate	A. Pendse, India
11.01.2022	Antiferromagnetic Skyrmions in Spin-Orbit Coupled Hund's Insulators and Metals	A. Mukherjee, India

3.1.7 Long-term Visitor Reports

Flat Bands: Interplay of Strong Correlations and Symmetries
Nisa Ara: May 6 – July 4, 2025

I. SUMMARY

1. Objectives of Proposed research:

i) Flat band engineering in two-dimensions featuring ultra-locality

ii) classification and identification of flat bands in higher-dimensional complex systems and the crossover within distinct compact localized states (CLS) generating prescriptions.

2. Background: In the field of condensed matter theory, CLS is a possible starting point for generating flat band systems and also classifying them. In one and two dimensions, flat band generators based on local connectivity and interference conditions are well established. In principle, these constructions can be generalised to higher-dimensional systems as well. Furthermore, the design of flat bands can also be approached algebraically, using nilpotent matrices to construct Hamiltonians with an extensive number of conserved quantities. This approach is well understood in one-dimensional models, such as the Creutz ladder, where

the interplay between lattice geometry and algebraic structure enables an exact realization of flat bands and CLS.

3. Disscusions:

(a) To explore and check possible connections with distinct CLS generators: We studied a one-dimensional diamond chain written in the tight-binding formalism. With a certain choice of parameters, the model exhibits three flat bands. Hamiltonian written in the real basis consists of the nearest neighbour hopping matrix, which becomes nilpotent, and the intra-cell hopping matrix remains Hermitian. The nilpotency of the matrix aligns with the claim we made earlier. We compare the set of CLS obtained by constructing compact Wannier functions and by obtaining the spinor which obeys supertranslation invariance, and work to find the mapping between the two if it exists.

(b) To show that strictly local projectors generate AFB systems in two dimensions. We work with a honeycomb lattice, and we impose periodic boundary conditions only in one direction. This results in a finite range hopping Hamiltonian in terms of k_x or k_y. To check if the norm of the CLS is k-independent.

4. Miscellaneous:

- I attended complex condensed matter systems (CCMS) team meetings, which led to open discussions and valuable feedback from other group members.
- I presented at the PCS weekly internal seminar. Title: Topological properties of low-dimensional many-body Hamiltonian.
- Discuss with Prof. Ki-Seok Kim (visitor at PCS), construction of flat bands in two dimensions using nilpotent matrices, which could also provide an excellent platform to study fractional Chern insulators.

II. FLAT BANDS IN ONE DIMENSION

Any generic free theory of two-component fermions on a one-dimensional lattice with nearest neighbour hopping (h.c. denotes a hermitian conjugate term):

$$H = \sum H_j\,; \quad \text{where} \quad H_j = \psi_{j+1}^\dagger q \psi_j + \text{h.c.}, \tag{1}$$

where H_j are the discrete version of Hamiltonian density and q is a 2×2 matrix

$$\dot{\psi}_j = -i(q\psi_{j-1} + q^\dagger \psi_{j+1}). \tag{2}$$

For an arbitrary choice of q, this free theory predicts the time evolution of an initially localized state should spread across further lattice points as expected for finite correlation length models. We note that if q is nilpotent then,

$$\ddot{\psi}_j = -\{q, q^\dagger\}\psi_j. \tag{3}$$

Given this condition, the state evolves to almost two neighbouring sites.

One of the most remarkable properties of the Hamiltonian (1) owing to the nilpotency of q is that the Hamiltonian densities at arbitrary points commute:

$$[H_i, H_j] = 0. \tag{4}$$

Hence, for any lattice function f, the operator:

$$Q_f = \sum_j f_j H_j \tag{5}$$

is a conserved charge. One can construct as many of such linearly independent charges as the number of lattice points. For arbitrary functions f, g, these charges also mutually commute: $[Q_f, Q_g] = 0$. To find the symmetries generated by the above charges, we define the transformation:

$$\delta_f \psi_j := -i[Q_f, \psi_j], \tag{6}$$

where the commutator, at the level of operators, means commutator with each component of the spinor ψ_j. Using fundamental canonical relations and the nilpotency of q together with the equation of motion (2), we arrive at:

$$\delta_f \xi_j = f_j \dot{\xi}_j, \qquad \text{where} \quad \xi_j = \frac{1}{\kappa}(q\psi_j + q^\dagger \psi_{j+1}). \tag{7}$$

This is a stationary state now, as $\xi_j = \dot{\xi}_j = \ddot{\xi}_j$. The new spinors ξ are the ones to produce CLS at the level of single-particle states. The Hamiltonian (1) in the form:

$$H = \sum_j \xi_j^\dagger (q + q^\dagger)\, \xi_j. \tag{8}$$

When expressed in terms of CLSs, the Hamiltonian clearly is a model of two non-dispersive or flat bands. To see this, let's parameterize the space of two-dimensional nilpotent matrices by two complex numbers (τ, α) as:

$$q = \tau \begin{pmatrix} 1 & \alpha \\ -1/\alpha & -1 \end{pmatrix}. \tag{9}$$

We discuss the two-component free fermion model defined by the Hamiltonian on a lattice called the Creutz ladder $\alpha = 1$. It is a paradigmatic one-dimensional lattice model that captures essential features of flat-band and topological physics in one dimension. The model consists of a two-leg ladder with cross-hopping terms. A key feature of the Creutz ladder is its ability to host flat energy bands, which arise due to perfect destructive interference in hopping paths. This results in compact localized states (CLS), where the wavefunction is localized over a finite number of sites despite the translational invariance of the system

$$H = \sum_j \Big[t_1 (c_{j+1}^\dagger c_j - d_{j+1}^\dagger d_j) + t_2 (c_{j+1}^\dagger d_j - d_{j+1}^\dagger c_j) + \text{h.c.} \Big]. \tag{10}$$

For flat bands we have $t_1 = t_2 = \tau$. The CLS modes $\xi^\dagger = (\alpha^\dagger \ \beta^\dagger)$ can be related to the site-local oscillators $\psi^\dagger = (c^\dagger \ d^\dagger)$ in (10) via the combinations:

$$\alpha_j = \frac{1}{2}(c_j + d_j - c_{j+1} + d_{j+1}), \qquad \beta_j = \frac{1}{2}(c_j + d_j + c_{j+1} - d_{j+1}). \tag{11}$$

In terms of the CLS, the Hamiltonian (10) takes the simple form:

$$H = 2\tau \sum_j (\alpha_j^\dagger \alpha_j - \beta_j^\dagger \beta_j). \tag{12}$$

III. FLAT BANDS IN TWO-DIMENSION

In systems with flat bands, electron dynamics become ultra-local; as electrons can't move due to the lack of dispersion, the Carroll symmetry naturally emerges [58]. This aspect of flat bands has been explored less and hence could be the starting point for constructing CLS, with the underlying Carroll of the theory. Consider the Hamiltonian on a two-dimensional square lattice:

$$H = \sum_{\mathbf{r}} \sum_{\mathbf{v}} \psi_{\mathbf{r}}^{\dagger} q_{\mathbf{v}} \psi_{\mathbf{r}+\mathbf{v}} + \text{h.c.}, \tag{13}$$

where $\mathbf{v}$ are the unit basis vectors of the lattice. For lattice spacing a, the basis vectors $\mathbf{v}$ are $\mathbf{x} = a\hat{\imath}, \mathbf{y} = a\hat{\jmath}$ and $q_{\mathbf{v}}$ is a 4×4 matrix. The Heisenberg equation of motion is:

$$\dot{\psi}_{\mathbf{r}} = -i \sum_{\mathbf{v}} \left(q_{\mathbf{v}} \psi_{\mathbf{r}+\mathbf{v}} + q_{\mathbf{v}}^{\dagger} \psi_{\mathbf{r}-\mathbf{v}}\right). \tag{14}$$

For an arbitrary choice of $q_{\mathbf{v}}$, this free theory predicts that the time evolution of an initially localised state should spread across further lattice points. However, with a careful choice of the $q_{\mathbf{v}}$ matrix, the time derivative of (14) can yield stationary states localised in space. For $\ddot{\psi}_{\mathbf{r}} = 0$, holds if:

$$\{q_{\mathbf{v}}, q_{\mathbf{v}'}\} = 0 = \{q_{\mathbf{v}}^{\dagger}, q_{\mathbf{v}'}^{\dagger}\}, \qquad \{q_{\mathbf{v}}, q_{\mathbf{v}'}^{\dagger}\} = \delta_{\mathbf{v},\mathbf{v}'}. \tag{15}$$

- To make a different choice of q matrix such that, CLS spans only one single site.
- To construct all-bands-flat systems, just using the representation of nilpotent matrices and, hence, a range of hoping parameters.
- Emergence of ergodicity with perturbation.

IV. FLAT BAND ENGINEERING IN DIAMOND LATTICE

Consider a system of N lattice sites,

$$H = \sum_{i=1}^{N} t(a_i^{\dagger} b_i + a_i^{\dagger} c_i) + t(c_i^{\dagger} a_{i+1} - b_i^{\dagger} a_{i+1}) + \text{H.c.} \tag{16}$$

In the momentum space, we have

$$H = \sum_k \begin{pmatrix} a_k^{\dagger} & b_k^{\dagger} & c_k^{\dagger} \end{pmatrix} \begin{pmatrix} 0 & t(1-e^{-ik}) & t(1+e^{-ik}) \\ t(1-e^{ik}) & 0 & 0 \\ t(1+e^{ik}) & 0 & 0 \end{pmatrix} \begin{pmatrix} a_k \\ b_k \\ c_k \end{pmatrix}, \tag{17}$$

where $\Psi_k^{\dagger} = (a_k^{\dagger}\ b_k^{\dagger}\ c_k^{\dagger})$ is a two-component fermion. Here a_k, b_k and c_k are the Fourier basis modes corresponding to the real space modes a_i, b_i and c_i, respectively, eg. $a_k = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} e^{-ikA_i} a_i$ etc. On diagonalizing 17, two energy bands are obtained in the new momentum basis α and β oscillators

$$H = \sum_k \begin{pmatrix} \alpha_k^{\dagger} & \beta_k^{\dagger} & \gamma_k^{\dagger} \end{pmatrix} \begin{pmatrix} 2t & 0 & 0 \\ 0 & -2t & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \alpha_k \\ \beta_k \\ \gamma_k \end{pmatrix}, \tag{18}$$

where we have two flat bands away from the Fermi level and one at the Fermi level.

Lets rewrite the Hamiltoninan in (16),

$$H = \sum_i \psi_{i+1}^{\dagger} q_1 \psi_i + \psi_i^{\dagger} q_2 \psi_i + \text{H.c.}, \tag{19}$$

where

$$q_1 = \begin{pmatrix} 0 & -1 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad q_2 = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}. \tag{20}$$

Here, q_1 is nilpotent but q_2 is not!.

A. Compact localised states
Bloch eigenfunctions are

$$u_1(k) = \begin{pmatrix} 0 \\ 1+e^{ik} \\ 1-e^{ik} \end{pmatrix}, \qquad u_2(k) = \begin{pmatrix} 2 \\ 1-e^{ik} \\ 1+e^{ik} \end{pmatrix}, \qquad u_3(k) = \begin{pmatrix} -2 \\ 1-e^{ik} \\ 1+e^{ik} \end{pmatrix}. \tag{21}$$

Since the Bloch functions are polynomials in $e^{\pm ik}$, their Fourier transform produces compact Wannier functions, given as

$$w_n(j) = \frac{1}{2\pi}\int_{-\pi}^{\pi} dk\, e^{ikj} u_n(k), \quad w_{1,j} = \begin{cases} (0,1,1)^T, & j=0 \\ (0,1,-1)^T, & j=1 \end{cases} \tag{22}$$

$$w_n(j) = \frac{1}{2\pi}\int_{-\pi}^{\pi} dk\, e^{ikj} u_n(k), \quad w_{1,j} = \begin{cases} (0,1,1)^T, & j=0 \\ (0,1,-1)^T, & j=1 \end{cases} \tag{23}$$

$$|\text{cls}\rangle_j = \sum_i w_n(i-j) x_i \tag{24}$$

$$|\text{cls}\rangle_1 = b_i + b_{i-1} + c_i - c_{i-1} \tag{25}$$

$$|\text{cls}\rangle_2 = -2a_i + b_i - b_{i-1} + c_i + c_{i-1} \tag{26}$$

$$|\text{cls}\rangle_3 = 2a_i + b_i - b_{i-1} + c_i + c_{i-1} \tag{27}$$

V. GRAPHENE SHEET

1. To check that to construct a 2d dimensional ABF model, the projectors are strictly local.

Consider a single layer of graphene with a finite number of lattice sites, whose tight-binding Hamiltonian is given by

$$H = t\sum_{i,\delta} a_i^\dagger b_{i+\delta} + b_i^\dagger a_{i+\delta} + \text{h.c.}, \tag{28}$$

where δ are the three nearest neighbours. We impose periodic boundary conditions in the x-direction only,

$$a_{x,y} = \frac{1}{\sqrt{N}}\sum_{k_x} e^{-ik_x x} a_{k_x,y} \tag{29}$$

$$H = t\sum_j c^\dagger_{2j,k_x} c_{2j+1,k_x} + c^\dagger_{2j,k_x} c_{2j-1,k_x}\left(e^{ika_1/2} + e^{-ika_1/2}\right) + \text{h.c.} \tag{30}$$

where $a_1 = \sqrt{3}a/2$ is and a is the graphene lattice constant. If $c_{2j-1} \to c_{2j-1}e^{ika_1/2}$, the (30) can be rewritten as

$$H = t\sum_j c^\dagger_{2j,k_x} c_{2j+1,k_x} + c^\dagger_{2j,k_x} c_{2j-1,k_x}\left(e^{-ika_1} + 1\right) + \text{h.c.} \tag{31}$$

Quantum Turbulence

Riccardo Ferrini: October 1 – December 20, 2024

My research project, under the supervision of Dr. Sergei Koniakhin, at the Center for Theoretical Physics of Complex Systems (PCS), during the third month of my visit, December 2024, was focused on deepening the analysis of Quantum Turbulence in Bose-Einstein Condensate of decaying polaritons.

In particular, briefly recalling my two previous reports, I developed first my analysis on studying the effect of radiative decay of polariton due to their finite lifetime on the creation and dynamics of vortex clusters (i.e., Quantum Turbulence) for a polariton BEC trapped in a hard-wall confining potential. The proposed model within our project consists in comparing three different stirring methods for the same polariton energetic-loss, which is considered occurring only during the second half of the simulation: the ratio between the mean densities at final and middle instants are 0.3, 0.1, 0.03, 0.01, and 0.000001, corresponding to the conservative case of long-living polaritons.

The stirring methods considered are the well-known rotation of spoon, by means of a rotating stirring potential; the imprinting of initial homogeneous configuration made of plane waves with same wavevectors but random directions, confined in square tiles; and the imprinting of an initial homogeneous state made of random-phase wavefunctions in squared pixels. The two last methods present a more instantaneous stirring effect of the condensate than the first technique, so this is why we compare the three methods only from the second half of the whole duration simulation, between 2.28 ns and 4.56 ns.

By means of vortex detection algorithm, we have continued inferring the vortex statics: the figure on the left shows the average initial distribution of vortices in configurations of single vortices, dipoles or clusters of different sizes for tile-imprinting and spoon stirring. It is then visible how these two methods are equivalent, and our proposed tile-imprinting scheme is a valid method for stirring. The picture on the right shows the time evolution of correlation function,

$$C = \frac{1}{N} \sum_{i=1}^{N} c_i,$$

with c_i the product of the circulation's signs of the ith vortex and its first neighbour. This physical quantity is important to understand how the vortex clustering is affected by the polariton decay: positive values of C correspond to a condensate state with clusters of vortices of the same signs, which correspond to a high-energetic and very-low-entropic configuration (negative temperatures), while negative values are associated to a randomly distributed configuration of vortex dipoles (high entropy and positive temperatures).

As the condensate depletes over time, the low polariton density causes a loss of incompressible kinetic energy of vortex clusters, causing density fluctuations, creating vortex dipoles and decreasing the order in the system: then for large polariton lifetime τ (i.e., $\tau = 300$ ns) the order is kept pretty well for the whole analysed interval, while as τ takes smaller values we register a faster decrease of the vortex ordering in the system towards a more disordered configuration of vortex dipoles and single vortices.

Control of the non-equilibrium polaritons condensation with injection of resonant pump

Aliaksei Osipau: November 6 – December 20, 2024

During my current stay in IBS I am involved in three scientific projects including: synchronization of ring-shaped exciton-polaritons condensate with resonant pumping, synchronization of two polaritonic spots, transition between graphene and random regular graphs with increasing spatial disorder.

Synchronization of ring-shaped exciton-polaritons condensate with resonant pumping

For this project I have calculated condensate spectrums in a presence of resonant pumping with different detunings. Calculated spectrums provide an evidence for the not-complete synchronization in the case when initial condensate's topological charge and resonant pump's topological charge are different leading to the formation of moving kinks. Kink's movement leads to the formation of the frequency combs besides main line corresponding to the coherent drive. The frequency comb size and repetitions rate depend on kink's velocity.

I have processed all results obtained current and during previous visit and made the draft of the paper which, after some corrections, would be submitted to the *Physical Review B* journal.

Synchronization of two polaritonic spots

I have conducted simulations, demonstrating different regimes of synchronization between two condensate spots with different spot sizes and pump powers. Including of the blue shift induced by dark reservoir significantly changes the condensate properties and synchronization switching regimes with increasing of pump's power. Then I have calculated condensate's spectrums for different distances between spots demonstrating anticrossing in the transition points.

Finally, I have studied the synchronization of two spots partially covered by resonant pumping. These simulations provide a possible experimental scheme for observation of synchronization of exciton-polaritons condensates with coherent drive which hasn't been observed before.

Transition between graphene and random regular graphs with increasing spatial disorder

I have written a code for studying of random regular graphs with different spatial disorder. Spatial disorder could be controlled with deformation of hexagonal grid applying condition of minimal distance between grid sides. After the deformation of hexagonal grid, the Voronoi tessellation was applied. Reducing the minimal distance condition, we can see the transition from ideal honeycomb lattice to random regular graphs. After the graph formation, I have studied properties of the obtained tight-binding Hamiltonians. I have studied spectrums and properties demonstrating localization properties of the modes such as inverse participation ratio (IPR). Using IPR, the transition from delocalized extended states of regular honeycomb lattice to localized states of random regular graphs was observed. Moreover, I have studied effects of boundary conditions on localization and observed that localization in the case of periodic boundary conditions is more pronounced than in the case of open boundaries.

Engineering fully flat bands and higher-order topology in the lattices of evanescently coupled multimode waveguides
Maxim Gorlach: March 12 – April 12, 2024

1. Flat bands and compact localized states in two-mode kagome lattice

I have carried on the theoretical analysis of flat bands and compact localized states arising in kagome lattice composed of evanescently coupled waveguides. Each waveguide hosts two degenerate modes with the different symmetry of the field further denoted as s and f orbitals.

Analysis revealed that it is possible to construct 6 different compact localized states meaning that all six bands in the spectrum of the two-mode kagome lattice become flat. Achieving such situation, however, requires fine-tuning of the parameters. Specifically,

- s and f modes of a single waveguide should be degenerate;

- coupling between adjacent s modes should coincide with the coupling between the adjacent f modes and should be equal to the inter-orbital coupling of s and f modes.

Numerical simulations suggest that these conditions can potentially be met in experimental situation allowing to demonstrate Aharonov-Bohm caging for the arbitrary excitation injected in such array of two-mode waveguides.

As a side observation, it is noted that the adjacent compact localized states corresponding to the same or different bands are mutually orthogonal, i.e. the scalar product of their quantum states vanishes.

2. Other examples of all-bands-flat lattices

I also examined another instance of all-bands-flat situation arising in the Lieb lattice with the degenerate s and p orbital modes at each site. Such system features three pairs of degenerate flat bands in the spectrum provided the parameters are fine-tuned accordingly. I have constructed the respective compact localized states. Similarly to the previous example, adjacent compact localized states appear to be mutually orthogonal.

These two instances of all-bands-flat lattices could be promising for the experimental implementation in the near future.

3. Construction of all-bands-flat system in 3D

An interesting question is whether it is possible to achieve all-bands-flat spectrum for a periodic 3D structure composed of the multimode meta-atoms. For that purpose, I examined pyrochlore lattice formed by the meta-atoms hosting degenerate modes described by the scalar spherical harmonics with $l = 0$ and $l = 3$ (two modes of such type are utilized).

Preliminary analysis suggests that it could be possible to construct 12 different compact localized states in such lattice ensuring that all bands in the spectrum become flat. Further confirmation in the tight-binding calculations is required.

If this approach will be successful, these results could provide a ground for the research paper showing the hierarchy of all-bands-flat lattices in 1, 2 and 3 spatial dimensions. In all cases, the dispersionless spectrum is ensured by the interference of the degenerate modes. This principle of constructing all-bands-flat spectra, to the best of my knowledge, is new and could be interesting to the community initiating further experimental studies.

As a specific implementation of the 3D proposal, I consider the acoustic platform, where the respective structures can be readily fabricated by the 3D printing technique, while the couplings can be flexibly controlled. This implementation requires further careful analysis including numerical simulations as well.

4. Effective Lagrangian description of topological multimode structure

I have analyzed theoretically the possibility to describe the topological structure based on the kagome lattice of evanescently coupled two-mode waveguides in terms of the effective Lagrangian introducing an effective gauge potential in the form of symmetric second rank tensor. This description allows one to apply field-theoretical concepts to topological systems and recover such important characteristics as bulk quadrupole moment, edge polarizations and corner charge. On the other hand, the value of the corner charge was known to me from the earlier independent calculation which yielded a quantized value of 0.5.

Compared to the Lagrangian description of the canonical quadrupole insulator, the effective Lagrangian of the designed multimode waveguide system should capture C_3 rotational symmetry of the structure. The derived Lagrangian appeared to be complex, creating further challenges in the theoretical description. This points towards some non-conventional type of topology in the system, which is probably not captured by the second rank tensorial effective gauge field and needs further refinement.

5. Corner charges and edge polarizations

I have analyzed the connection between the corner charges at nonrectangular corners of topological structures, bulk quadrupole moment and edge polarizations. Analysis showed that both bulk quadrupole moment and edge polarizations are dependent on the choice of the system of Wannier functions. Hence, these gauge-dependent quantities are not physical observables. However, their sum yields the value of the corner charge which is gauge-invariant quantity.

My analysis was focused on the question, which component of the bulk quadrupole moment should be computed in order to recover the correct value of the corner charge. It appears that the relevant component of bulk quadrupole moment is a linear combination of diagonal and off-diagonal quadrupole moment components with the coefficients depending on the opening angle of the respective corner.

Synchronization stimulates organization of active matter and Non-equilibrium dynamics of polariton condensates.

Igor Aronson: November 15 – December 20, 2023

During my stay in PCS IBS, I presented one scientific seminar, two pedagogical lectures, and initiated two new collaborations.

Seminar: Hierarchical Organization of Communicating Active Swarms

Abstract: Active matter (collectives of self-propelled particles) spontaneously organizes into large-scale coherent swarms. Living organisms use communications and information processing to enhance their evolutionary competitiveness. This feature is mostly lacking in synthetic active matter, e.g., simple microrobots, while it could significantly improve their functionality and efficiency. Using a simple description of self-propelled interacting particles (so-called Vicsek model) complemented by coupling to a signaling field, we have shown that chemical communication with decision-making at individual agents' level enables a multiscale organization. In the case of agents with long-range communications, we considered the self-organization of coupled self-propelled nonlinear oscillators emitting acoustic waves. We discovered spontaneous assembly into localized droplets and collectively propagating snake- and larvae-like solutions. These structures demonstrate collective navigation in heterogeneous environments and threat detection. Our results provide insights into the emerging functionality of synthetic non-equilibrium systems such as micro-robotic swarms capable of processing information and making decisions.

Two lectures on the Introduction into the Complex-Ginzburg-Landau Equation

The cubic complex Ginzburg-Landau equation is one of the most-studied nonlinear equations in the physics community. It describes a vast variety of phenomena from nonlinear waves to second-order phase transitions, from superconductivity, superfluidity, Bose-Einstein and polariton condensation to liquid crystals and strings in field theory. I gave an overview of various phenomena described by the complex Ginzburg-Landau equation in one, two, and three dimensions from the point of view of condensed-matter physicists. The aim was to study the relevant solutions in order to gain insight into nonequilibrium phenomena in spatially extended systems.

- Introduction
- Simple Model – Rich Phenomenology
- Plane Waves and Their Stability
- Absolute vs Convective Instability
- Topological Defects, Sinks and Sources
- Core Instability of Defects
- Unsolved Problems

Initiated collaborations

Nonequilibrium polariton condensates. I initiated a new collaboration with Drs. Sergei Konyakhin, Oleg Utesov, and Prof. Boris Altshuller on the non-equilibrium dynamics of 2D polariton condensates described by the complex Ginzburg-Landau equation in the weak dissipation limit:

$$\psi_t = (i + \varepsilon_1)\nabla^2\psi + \Gamma(r)\psi - (i + \varepsilon_2)\psi|\psi|^2, \tag{1}$$

where $\Gamma(r)$ describes the (incoherent) pumping profile, and $\varepsilon_1 \neq \varepsilon_2 \ll 1$ describe the contributions from the dissipative processes. Without these coefficients, Eq. (1) exhibits highly turbulent dynamics. The purpose of the study was to engineer a pumping profile $\Gamma(r)$ that would generate a quasi-stationary spatial distribution of the condensate density $|\psi|^2$. The quasi-stationary distributions are appealing because they can be observed experimentally. We proposed to consider an imperfect ring pumping. An imperfection (a small dimple in the pumping intensity) was required to stabilize and pin an array of dark solitons. To investigate the problem, I developed a numerical algorithm that was shared with the collaborators. Preliminary results indicate a formation of a "vortex fountain," a structure that ejects vortices through the dimple in the profile. For certain values of the parameters $\varepsilon_1, \varepsilon_2$, the vortex fountain yields a quasi-stationary condensate density distribution that can be detected experimentally.

We also considered interacting polariton condensates with orthogonal polarizations:

$$\psi_{1t} = (i + \varepsilon_1)\nabla^2\psi_1 + \Gamma(r)\psi_1 - (i + \varepsilon_2)\psi_1(|\psi_1|^2 + g|\psi_2|^2), \tag{2}$$

$$\psi_{2t} = (i + \varepsilon_1)\nabla^2\psi_2 + \Gamma(r)\psi_2 - (i + \varepsilon_2)\psi_2(|\psi_2|^2 + g|\psi_1|^2). \tag{3}$$

Analysis of Eqs. (2) and (3) demonstrated the formation of domains of orthogonal polarizations for $g > 1$. In the large-time limit, only one polarization survives. If the coupling parameter $g < 1$, the two condensates co-exist, and asymptotically, $|\psi_1|^2 = |\psi_2|^2$.

We approached the experimental group of Prof. Hyoungsoon Choi (KAIST) and had a meeting with him and his group. Prof. Choi indicated interest to conduct experiments for polariton condensates in the imperfect ring configuration. Such configuration can be created by the LC digital light modulator.

Overall, we plan to investigate Eqs. (1)–(3) in a wide range of parameters to establish the most experimentally observable regimes. We will derive the values of the dissipative coefficients from the first-principle models and determine their dependence on the temperature and other material parameters. We will interact with experimentalists and provide theoretical support in finding long-living spatially heterogeneous condensates.

Thermalization and energy cascades in nearly integrable deterministic systems. I initiated collaboration with Drs. Gabriel Lando and Sergej Flach. Recently, Drs. Lando and Flach have studied the energy equipartition and thermalization in nearly integrable Hamiltonian systems. Thermalization occurs if the integrability limit is slightly perturbed. An interesting question in this context is the behavior of open systems. For example, as in hydrodynamic turbulence, one may introduce energy injection at large scales and energy dissipation at small scales. In general, one would expect the emergence of an energy cascade and Kolmogorov-like power-law energy spectra. That is realized in the so-called shell model of turbulence that resembles the Fermi-Pasta-Ulam chain. However, the effect of integrability could be more subtle and may lead to the energy pileup rather than the cascade. We plan to elaborate on this intriguing question.

Fermi-Pasta-Ulam-Tsingou problem and Raman spectra in finite-size crystallites
Tomasz Bednarek: July 17 – September 16, 2023

1. Fermi-Pasta-Ulam-Tsingou problem status

We have started with Dr. S. V. Koniakhin's code for nanodiamond vibrational modes calculation (in harmonic approximation) in Mathematica, yet I rewrote it in order to fully incorporate the Keating's model in accordance with the Anastassakis' fit [*Phys. Rev. B* **41**, 7529] as well as the Cousins' fit [*Phys. Rev. B* **67**, 024107]. As the zone-center optical phonon frequency is different from the highest eigenfrequency from the force-constant real-space dynamical matrix, I calculated the phonon dispersion curves for diamond from both fits and scaled them to the experimentally known value of 1332 cm^{-1}. Due to the numerical-divergence problem I mentioned in the mid-term report, Dr. S. V. Koniakhin suggested we reimplement the code from the Hamiltonian-based approach to the force-based one which works consistently for the stretching forces, yet with the bending forces it poses quite a problem (for now) in terms of the reimplementation. However, we were already able to obtain the revival-like behavior of the highest-mode excitation for a specific size of a nanodiamond (it was 6$\times$ nearest-neighbour distance, and for other integer multiples the revivals looked different in each case).

2. Gross-Pitaevskii-equation problem status

A few quantum systems have been tested in order to generate quantum vortices (like the Gaussian-filtered uniformly randomised wavefunction), yet finally the vortices have been obtained for the alternative systems like the standard rotating spoon scheme and the wavefunction imprinted with different wavevectors on a square grid. Moreover, the efficiency test was prepared for the PyTorch GPU GPE solver versus Matlab's GPU GPE solver for the conditions of the so-called snake instability.

3. Additional researched problem: graphene-on-the-substrate problem

I have been additionally tasked with checking the Monte Carlo-based homemade code of the 3002-atom graphene sheet placed on the 7764-atom diamond substrate, and checking the force constants (responsible for stretching, bending, and Van der Waals interaction). There were two approaches initially assumed — one based on the well-known DREIDING molecular force-field approach, and the other based on the *ab initio* calculations of the Van der Waals as well as the usual force constants. It finally occurred that the DREIDING approach will be used due to the switch to the amorphous SiO_2 substrate (containing 6552 atoms) and the need for consistency of the used VdW parameters. The force constants were checked analytically by investigating the smallest possible atom systems for which the necessary properties emerge. Moreover, the whole large-system simulation was thoroughly debugged and optimised in order to yield results in the most efficient way using the available 48 CPU-core IPC PAS computing cluster. The possible future paper will shed light onto the microscopic level of graphene–substrate interaction and phonon and profile corrugation transfer from the substrate to graphene.

4. Additional researched problem: surface phonons on Pt(111)

According to Gawronski *et al.* [*Nano Lett.* **11**, 7, 2720–2724 (2011)], if the STM bias voltage is set appropriately, only then it is possible to observe Friedel oscillations around an adsorbed molecule. They attribute this phenomenon to the electron–phonon coupling described by the Holstein Hamiltonian. We wanted to check if such a phenomenon would also occur for our investigated CO/Pt(111) case, and for this reason we studied the surface phonons on Pt(111). After thorough testing, it occurred that from all three papers we found, only the one [*Surface Science* **53**, 252–278 (1976)] suggested by my supervisor Dr. Alexandra Siklitskaya nicely reproduced the experimental phonon dispersion curves of bulk Pt. Right now I am trying to obtain the surface phonons for Pt(111), which requires computation of many layers going deep into the bulk. Important discussions on nanoparticle/periodic-system approaches were also held.

5. Additional scientific activities

I gave the visitor seminar to the PCS center on September 7 (Thursday) about the topic of constructing a simple model of the 3D surface response to an external electric charge, which was a basis of my MSc thesis and now is being developed further in my PhD research. The questions asked during the seminar were quite important, as they reflected some possible caveats of the aforementioned model. Moreover, it sparked discussion on how to progress further with it, and how to tackle the easy-sounding, yet not-so-simple in practice problem of analytically modelling the surface termination of the bulk — especially I would like to thank Dr. Sonu Verma for his brilliant idea which may help us finally overcome the obstacle of the vacuum–bulk potential transition being literally hard to analyse analytically.

Moreover, thanks to the PCS center's generosity, I was also able to attend the *International Workshop on Polaritons in Emerging Materials* taking place on September 11–15 at PCS-IBS. The lectures, posters, and discussions were really intriguing and broadened the scope of my knowledge in terms of the exciton–polariton field. Moreover, I was able to meet with plenty of scientists with whom I held fruitful scientific discussions such as Prof. Yong-Hoon Cho and Dr. Helgi Sigurdsson.

Disorder and attractive Hubbard-type interaction in transport and localization on flat bands

Chan Si Min: April 2 – June 30, 2023

Along with Professors Sergej Flach and Alexei Andreanov as well as my advisor George Batrouni, I have completed a project regarding superconductivity on Wannier-Stark flat bands in two and three dimensions.

In particular, the Wannier-Stark flat bands provide a nice control over the wavefunction spread and the number of flat bands that contribute towards the superfluid weight. At weak DC field strengths, the superfluid weight is dramatically enhanced. We performed computations on both 2D and 3D systems, both of which show similar qualitative dependence on the DC field strength and Hubbard attraction strength. At weak interaction, the superfluid weight diverges with the DC field strength approximately with an inverse proportionality, due to the single-particle wavefunction.

To understand the Cooper pair coupling, we also computed the pairing order parameter and correlation functions. We showed that the correlation functions in the presence of interaction behave very differently along and perpendicular to the DC field direction. Along the field direction, it decays like the single-particle wavefunction with a factor difference. Perpendicular to the DC field direction (in the flat band direction), it becomes an exponential decay, and we extract the correlation lengths. As both the interaction and DC field strength go to zero, the pairs converge to the square lattice limit, with a large correlation length and small pairing order parameter. This contrasts with the superfluid weight which is enhanced with decreasing DC field strength.

Thus, we propose that an intermediate DC field strength should be chosen to obtain large values for both the pairing order parameter and the superfluid weight.

Our results show that flat band superconductivity does not simply depend on geometrical and topological properties of the bands as previously proposed. We demonstrated that even with a trivial lattice, flat bands that arise from the application of a static field result in enhanced superconductivity too. We conclude that it is more important to have wavefunction overlap in the single-particle limit than the topology of the lattice.

We have found interesting results using mean-field computations as highlighted above and have prepared a manuscript which will be ready for submission soon.

Physical observability of mathematical features
Henning Schomerus: February 1 – March 31, 2023

Prof. Henning Schomerus focused their research work at the PCS on the following projects:

1. Pseudo-Landau levels in graphene

They identified curvature corrections in continuum theory and curvature signatures in the pseudo-Landau-level (pLL) degeneracy, as well as the role of half-flux vortices. They obtained an exhaustive analytical understanding of the single-particle theory, including in the case of an additional external magnetic field. These results match perfectly with numerical results on finite systems. They furthermore explained numerical results for the many-body case, evaluated in the context of Kitaev's honeycomb system. They completed a first draft of an exhaustive paper, and all that remains is to complete this and submit it for publication. They also discussed a wide range of extensions, including to quantum transport in graphene and ways to engineer fractional quantum Hall physics.

2. Descriptions of flat bands within a real-space renormalization approach

The approach turns out to give new insights. He illustrated with a simple model how boundaries that break compactons result in an exponentially decaying state whose intensity decay can be precisely obtained from a simple calculation. They plan to extend this to richer models, including those that support compactons over several unit cells. They also looked at the role of flat bands themselves and found that the approach reproduces known results consistently. They will next explore whether they can also obtain new information from this, and shared a working draft to turn this project into a paper.

3. Non-Hermitian bulk boundary correspondence

They found that their approaches tackle this problem in complementary ways, and combining them into one picture promises significant new insights. To facilitate this, they have started to apply their method to a model.

4. Nonreciprocal and non-Hermitian scattering and transport

The role of the left scattering functions is not fully understood. They know of strict relations between the left and right scattering matrices and how they appear in certain physical quantities, but it would be useful to establish their general physical meaning. This is a deep question, which they plan to continue discussing, and could lead to a completely new physical perspective.

5. Random-matrix approach to nonergodicity transitions

A diagrammatic approach in which one can use random-matrix theory was suggested, and they discussed in detail how this could be used to push investigations to large system sizes. They shared notes on Overleaf for further development.

Deep learning of the quantum Wigner crystal formation in a two-dimensional electron system

Victor Kagalovsky: February 4 – March 8, 2023

Prof. Victor Kagalovsky focused their research work at the PCS on the following projects: fractional conductance in the strongly interacting one-dimensional (1D) system. This research considers a strongly interacting one-dimensional system with N channels. They studied the conditions necessary for the coexistence of various perturbations. The neutrality requirement restricts the most general interaction (beyond forward-scattering quadratic terms in the Lagrangian), meaning that each term in the Hamiltonian conserves the number of particles. To become relevant and open a gap, the perturbation has to represent a new field, and new fields have to preserve the form of the Lagrangian. Another constraint (formulated by Haldane) is on the type of perturbations allowed to coexist.

The conductance (in e^2/h units) of the remaining free fields can be presented as the difference between the initial conductance of all N channels and the conductance eliminated by K compatible relevant perturbations which freeze K corresponding fields. The variety of possible combinations of the relevant perturbations provides a variety of possible fractional conductances. It turned out that relevant perturbations do not define the remaining conducting channels univocally. In the system with N channels, the matrix describing the new basis of gapped and conducting channels is $2N \times 2N$. It has $4N^2$ elements. If there are $K < N$ relevant perturbations, they knew all $2KN$ elements in the first K lines. When they use all equations following the conditions, the matrix M must satisfy we still have $2(N-K)(N-1)$ degrees of freedom. They have found the most general expression of matrix M for a system with two channels and one relevant perturbation. It has two degrees of freedom as follows from the expression. The conductance of the remaining free channels depends on two parameters. The experimental results support the idea of spontaneous symmetry breaking when a system chooses a particular combination of conducting channels.

Prof. Victor Kagalovsky also focused their research work at the PCS on the following projects: implementation of machine learning to a set of perturbed quadratic Sachdev-Ye-Kitaev (SYK) Hamiltonians defined on graphs. The related numerical methods require colossal memory and time, significantly limiting the number of particles. Their idea is to teach a computer to define whether the system is localized or chaotic based on the set of random numbers generated to determine the Hamiltonian without numerical evaluation of r-ratios. If successful, this method will allow for studying many-body problems in systems with many particles.

Trotter error and integrable nonautonomous Hamiltonians
Emil Yuzbashyan: October 14 – November 20, 2022

Prof. Emil Yuzbashyan has studied integrable nonautonomous Hamiltonians. A major recent breakthrough has been the explicit solution for the long-time dynamics of several important nonautonomous quantum Hamiltonians, such as the BCS Hamiltonian with coupling inversely proportional to time. These are also interesting models of quantum adiabatic computations. On the other hand, in quantum computing, continuous-time evolution is discretized through an approach known as trotterization. As the discretization step tends to zero, the discrete and continuous-time evolutions should converge.

The main open problem in this field is to understand the trotterization error. They believe this error should behave very differently with the system size and discretization step for integrable and chaotic systems, as the discretization itself breaks integrability. This problem has similarities with the famous Fermi-Pasta-Ulam problem and the discrete nonlinear Schrödinger equation, except that in our case the Hamiltonian is quantum and time-dependent, and the discretization procedure is different. He discussed the theory of Trotter error with IBS PCS members.

Prof. Yuzbashyan has also studied and discussed how strong the electron–phonon interaction in metals can be and quantum integrability. He showed that the dimensionless electron–phonon coupling λ cannot exceed a certain critical value in metals. Increasing λ beyond this value leads to a structural instability accompanied by a metal–insulator transition. This also implies an upper bound on the superconducting T_c in units of the characteristic phonon frequency in conventional superconductors. He compared the upper bounds on λ and T_c with existing experimental data.

In addition, Prof. Yuzbashyan participated in PCS seminars and discussion meetings on many related topics at PCS. He also gave an invited talk entitled "Is Nonequilibrium Superconductivity a Quantum or a Classical Phenomenon?" and participated in valuable discussions at the *Dynamics Days Asia Pacific (DDAP12)* conference.

Analysis of experimental data for open quantum graphs with symplectic symmetry and development of a random-matrix theory description
Jiongning Che, Xiaodong Zhang: Sep. 25 – Dec. 12, 2022

Generally, in experiments with microwave networks one cannot achieve a perfect coupling of measurement, so we first need to remove the direct process:

$$s^{kk} = \frac{1 - z^{kk}}{1 + z^{kk}}, \tag{1}$$

to extract the scattering matrix s^{kk} of a network for the perfect coupling case. In this formula, z^{kk} denotes the normalized impedance:

$$z^{kk} = \frac{\mathrm{Re}\, Z^{kk} + i(\mathrm{Im}\, Z^{kk} - \mathrm{Im}\, Z_r^{kk})}{\mathrm{Re}\, Z_r^{kk}}, \tag{2}$$

where $Z^{kk} = Z_0(1 + S^{kk})/(1 - S^{kk})$ and $Z_r^{kk} = Z_0(1 + S_r^{kk})/(1 - S_r^{kk})$ are the network and the radiation impedances expressed by the measured and the radiation scattering matrix elements S^{kk} and S_r^{kk}, respectively. Z_0 is the characteristic impedance of the transmission lines feeding the T-joint vertices. S_r^{kk} is the scattering matrix measured at the input of the coupling structure for the same coupling geometry, but with the vertices of the system removed to infinity (we connect two 50 Ω loads to T-joints).

Secondly, we will process the data and determine the distributions as follows. The

Wigner reaction matrix K is related to the scattering matrix S by the following relation:

$$S_{aa} = \frac{1 - iK_{aa}}{1 + iK_{aa}}, \tag{3}$$

if S is diagonal, as is the case in the network with symplectic symmetry. We will analyse the distributions of the real part $u = \mathrm{Re}\, K$ and the imaginary part $v = -\mathrm{Im}\, K$ for different absorption.

In the one-antenna case, the S matrix can be parameterized as

$$S = \sqrt{R} e^{i\theta} = r e^{i\theta}, \tag{4}$$

where R is the reflection coefficient, r is the modulus, and θ the phase. We also investigate properties of the S matrix. The aim is a comparison with random matrix theory results.

Quantum transport of Bose and Fermi particles across non-trivial 1D and 2D lattices

Andrey Kolovsky: September 17 – December 14, 2022

Prof. Andrey Kolovsky has studied transport of Fermi and Bose particles in non-trivial lattices. Here “non-trivial” means that the Bloch states of a quantum particle in the lattice possess topological properties, or that the Bloch spectrum includes Dirac cones or flat bands. To address the transport problem in full detail, one needs to include into consideration particle reservoirs or a battery, which serve as the particle source and drain. In the physical literature, this setup is mostly analyzed for Markovian reservoirs and simple one-dimensional lattices. Exceptions are the previous works where he considered the flux rhombic lattice connected to Markovian reservoirs, and the studies which considered the simple one-dimensional lattice connected to non-Markovian reservoirs. He has studied transport in the flux rhombic lattice (and similar quasi-1D lattices with flat bands) attached to non-Markovian reservoirs and extended these studies to the case of two-dimensional lattices.

Effect of inter-particle interaction on the transport of Bose particles from the viewpoint of laboratory experiments with superconducting circuits

Prof. Kolovsky has studied the effect of inter-particle interaction on the transport of Bose particles from the viewpoint of laboratory experiments with superconducting circuits. Recently, much attention has been paid to lattices where all Bloch bands are flat. A famous example of such a lattice is the diamond or π-flux rhombic lattice (where the term “π-flux” means that the sum of phases of the nearest-neighbor hopping matrix elements equals π). All eigenstates of the quantum particle in this lattice are compact localized states, which prohibit any transport across the lattice. This statement, however, is valid only for non-interacting particles, and a finite inter-particle interaction may recover the transport.

In the present work, they address the effect of inter-particle interaction on the transport of Bose particles from the viewpoint of laboratory experiments with superconducting circuits. In these experiments, one arranges transmons (Josephson-junction-based quantum nonlinear oscillators) into a lattice, where the first transmon in the lattice is excited by a microwave generator, and the transmitted signal is read from the last transmon.

Due to the presence of dissipation (more precisely, contraction of the phase volume), the dynamics of the system is determined by attractors of different types, which can be sorted into “symmetric” and “asymmetric” attractors. The asymmetric attractors are found by solving the system of nonlinear algebraic equations obtained by setting its left-hand side to zero. Another asymmetric attractor (i.e., another solution of the algebraic equations) is obtained by the symmetry transformation. They stress that these attractors are responsible for the non-zero current across the diamond lattice, and they have verified that these attractors are also present in the lattice consisting of more than one rhombus.

Insulator-to-conductor transition for interacting bosons in a flat-band lattice

Prof. Kolovsky has studied the transport of interacting Bose particles across the diamond lattice. This system possesses two unique properties: (i) the π-flux symmetry of the lattice, which prohibits any transport of non-interacting bosons; (ii) chaotic mean-field dynamics in the case of vanishing dissipation and finite inter-particle interactions. Because of (i) and (ii), the system shows very unusual dissipative dynamics, resulting in a random steady state that can be either insulating or conducting. The results of the mean-field analysis are compared with those of the pseudoclassical approach and the exact solution of the master equation for the density matrix of Bose particles.

They addressed the effect of inter-particle interaction on the transport of Bose particles across the diamond lattice from the viewpoint of laboratory experiments where bosons are injected into the first site of the lattice using an external coherent drive and withdrawn from the last site. Nowadays, such experiments can be performed using various physical platforms, for example, superconducting circuits. Briefly, one arranges the transmons (microresonators coupled to Josephson junctions) in a lattice, drives the first transmon using a microwave field generator, and reads the signal from the last transmon. The crucial ingredient of the system is that Josephson junctions introduce effective inter-particle interactions for photons in the microresonators and, hence, the system can be described by the Bose-Hubbard Hamiltonian.

Another promising system is photonic crystals. In this context, they studied a recent laboratory experiment where the π-flux rhombic lattice was realized and the absence of transport for non-interacting photons was experimentally confirmed.

3.2 Distinguished PCS Postdoctoral Research Fellows

The Center offers Distinguished PCS Postdoctoral Research Fellow positions for experienced postdoctoral scientists. The Distinguished PCS Postdoctoral Research Fellows conduct independent studies, complement research areas pursued at the Center, and participate in the co-supervision of PhD students. At the PCS we count two Fellows: Dr. Tilen Čadež and Dr. Ki Hoon Lee (moved to a faculty position at Incheon Nationl University, Korea, in August, 2020).

Dr. Tilen Čadež

The activities within the Center for Theoretical Physics of Complex Systems (PCS IBS) started on Feb. 1. 2020 in the departmental research team Complex Condensed Matter Systems (lead by S. Flach and A. Andreanov). The main research topics of interest are disorder, quantum chaos, flat bands, driven quantum systems and machine learning. On the topics of flat bands and disorder there was active co -advising of Dr. Yeongjun Kim (started in fall 2020, finished in fall 2024). Between January 2021 – January 2025 he took the duty of the PCS seminar master and hosted the PCS talks and colloquiums (most of which are archived and can be viewed at PCS IBS youtube channel:
https://www.youtube.com/channel/UC0c8V38r5QOGgrlnsu-nREA).

Five publications were co-authored and published (4 in Physical Review B, 1 in New Journal of Physics):

- The Rosenzweig–Porter model revisited for the three Wigner–Dyson symmetry classes, T Čadež, DK Nandy, D Rosa, A Andreanov, B Dietz, New Journal of Physics 26 (8), 083018, (2024).

- Enhancement of superconductivity in the Fibonacci chain, M Sun, T Čadež, I Yurkevich, A Andreanov, Physical Review B 109 (13), 134504 (2024).
- Machine learning wave functions to identify fractal phases, T Čadež, B Dietz, D Rosa, A Andreanov, K Slevin, T Ohtsuki, Physical Review B 108 (18), 184202, (2023).
- Flat band induced metal-insulator transitions for weak magnetic flux and spin-orbit disorder, Y Kim, T Čadež, A Andreanov, S Flach, Physical Review B 107 (17), 174202, (2023).
- Delayed thermalization in the mass-deformed Sachdev-Ye-Kitaev model, DK Nandy, T Čadež, B Dietz, A Andreanov, D Rosa, Physical Review B 106 (24), 245147, (2022).

From January 2022 he participated in several events and scientific visits:

- June 2024, International Workshop on Disordered Systems 2024, University of Salamanca, Spain
  Invited talk: Machine Learning Ergodicity Breaking Transitions
- June 2024, J. Stefan Institute, Ljubljana, Slovenia
  Seminar: Machine Learning Ergodicity Breaking Transitions
- November 2023, Asian Network School and Workshop on Complex Condensed Matter Systems, Vietnam Academy of Science and Technology (IOP-VAST), Hanoi, Vietnam
  Invited talk: Machine learning wave functions to identify fractal phases
- September 2023, JPS 78th Annual meeting, Tohoku University, Sendai, Japan
  Contributed talk: Machine learning wave functions to identify fractal phases
- September 2023, Sophia University, Tokyo, Japan
  Seminar: The Rosenzweig Porter model revisited for the three Wigner-Dyson symmetry classes

3.3 Appointments and Awards

Since the foundation of the PCS, sixteen research fellows moved to faculty positions outside IBS. *Gentaro Watanabe* left our Center in February 2016 for Zhejiang University (Hangzhou, China), where he was offered a ZJU 100 Young Professorship (Hundred Talent Program). In August 2017, *Nojoon Myoung* joined the faculty at Chosun University, Korea. *Pinquan Qin* moved to a faculty position at Wuhan University of Technology, China, in May 2018. *Ara Go* moved to a faculty position at Chonnam National University, Korea, in August 2020. *Ki Hoon Lee* moved to a faculty position at Incheon National University, Korea, in August 2020. *Kun Woo Kim* moved to a faculty position at Chung-Ang University, Korea, in March 2021. *Ajith Ramachandran* moved to a faculty position at Christ College Irinjalakuda, India, in September 2021. *Meng Sun* moved to a faculty position at Beijing University of Technology, China, in October 2021. *Diana Thongjaomayum* moved to a faculty position at Tezpur University, India, in December 2021. *Ivan Savenko* moved to a faculty position at Guandong Technion Israel Institute of Technology, China, in February 2023. *Hee Chul Park* moved to a faculty position at Pukyong National University, Korea, in March 2023. *Moon Jip Park* moved to a faculty position at Hanyang University, Korea, in March 2023. *Dario Rosa* moved to a faculty position at University Estadual Paulista São Paulo, Brazil, in October 2023. *Dominik Šafránek* moved to a faculty position at Charles University, Czechia, in July 2025. *Jae-Ho Han* moved to a faculty position at Korea Military Academy, Korea, in August 2025. *Dung Xuan Nguyen* moved to a faculty position at International Centre for Interdisciplinary Science and Education (ICISE), Vietnam, in September 2025.

The *University of Science and Technology (UST)* appointed the following PCS researchers as faculty members: *Alexei Andreanov, Sergej Flach, Hee-Chul Park, Moon Jip Park, Jung-Wan Ryu, Dario Rosa, Ivan Savenko, Barbara Dietz, Dung Xuan Nguyen, Sergei Koniakhin, Dominik Šafránek.*

3.4 Teaching and Education

We host three main categories of young researchers – PhD students, young postdocs (with typically less than 2 years postdoctoral experience), and student trainees (usually PhD students researching at PCS for a limited time while being enrolled at another university either in Korea or abroad).

PhD students. Each student has a main supervisor and a co-supervisor. Research project discussions take place on a daily basis. All enrolled UST students take courses within UST. One of our research fellows (Jung Wan Ryu) is the center's UST coordinator and ensures a smooth operation of all UST related activities in close and permanent contact with all our PhD students and the UST office. Starting from 2017 we run graduate lecture courses at our center, as part of the UST curriculum. All our PhD students are required to take these courses, which are also open to other UST PhD students. We encourage participation in topic-relevant winter and summer schools, both in Korea and abroad. Once at least one research project is close to finalization and a manuscript is submitted, we also encourage participation in topic-relevant workshops and conferences with a poster or contributed talk presentation. Talks are prepared jointly with the supervisor, and talks rehearsals are conducted with the team to ensure highest presentation quality.

Postdocs. Each Postdoc joins at least one of the teams, and has at least one project supervisor (director and team leaders). Research project discussions including team discussions and team meetings take place on a daily-to-weekly basis. We encourage participation in topic-relevant winter and summer schools, both in Korea and abroad. Once at least one research project is close to finalization and a manuscript is submitted, we also encourage participation in topic-relevant workshops and conferences, both in Korea and abroad, with a poster, contributed (or even invited) talk presentation. Each postdoc is requested to write an annual report on his/her research activity including the research project plans for the next year, with a subsequent personal discussion with the director.

PhD Students and Postdocs. Research projects with Korean and/or international collaboration are strongly encouraged. All young researchers deliver two talks per year at the weekly PCS Internal Seminar. A center library with topic-relevant monographies can be used by all center members. Our PCS Visitors Program is offering free participation in international workshops/conferences (20-30 invited talks per workshop/conference, four-five meetings per year), and in PCS seminars delivered by Korean and international visitors (30-40 talks annually). Young researchers discuss with invited workshop speakers during ample discussion slots, and engage in research discussions with Advanced Study Group members, and short and long term visitors. A number of joint research collaborations did occur from this cross-fertilization already, and will continue to occur at an even higher rate in the future. Young researchers participate in our annual 2-3 days PCS retreat, during which research presentations and other activities support the formation of a healthy center team. In addition, we regularly join with all center members during monthly center dinners.

Our Center was hosting ten Ph.D. students. All are part of the IBS School, a Graduate School with enrolment at the *University of Science and Technology* (UST). To ensure highest standards of Ph.D. training for all IBS School students, we offer lecture courses on a regular semester basis since 2017. Course topics are closely related with the PCS research areas. *Alexei Andreanov, Sergej Flach, Hee-Chul Park, Moon Jip Park, Jung-Wan Ryu, Dario Rosa, Ivan Savenko, Barbara Dietz, Dung Xuan Nguyen, Sergei Koniakhin, Dominik Šafránek* are full-time faculty members of the UST.

All members of the Center are required to participate in the Friday internal seminar, where each member is scheduled to give a 15 minutes talk followed by an unlimited discussion. In addition, we hold annual retreats where short talks are given by all PCS members, as well as guests from the Asia Pacific Center for Theoretical Physics (APCTP). The PCS research teams schedule their work meetings autonomously. The division team meets regularly once a week, with young postdocs and Ph.D. students reporting on their work.

All Ph.D. students participate in the annual Asian Network School, where several of our team leaders serve as lecturers. All young researchers are required to submit abstracts and present their ongoing research at the annual meetings of the Korean Physical Society.

3.5 Equipment and Premises

3.5.1 Computing Facilities

Computational facilities are vital for successful research in the field of theoretical physics of complex systems. For general computational tasks, we are offering a Linux based cluster – currently with 75 nodes, 2 CPUs per node, 12 & 14 & 20 cores per CPU, i.e. a total of 2104 cores, and 64 GB & 256GB memory per node. For specific tasks, such as long time integrations of coupled ordinary differential equations with limited RAM need, we offer 2 GPU clusters with about 33,408 GPU cores. Furthermore, we have installed 8 high performance desktops (nodes), with 512 GB memory each for high performance computations requiring large memory capacity, and also for running test jobs before submitting to the cluster. Access to the above infrastructure is provided with NFS clients installed in all offices. The computational library includes a number of different products, among them – due to an increasing demand – various integrated software environments. We aim at a further increase of the size and performance of our computational facilities as the Center continues to grow.


3.5.2 Hybrid-Conference system

Since the installation of the hybrid conference system for video conferencing in the PCS seminar room, all international workshops and seminars, as well as the 2022 SAB meeting, have been organized in hybrid mode. In particular, in 2024, we successfully held the Intercontinental Binodal Workshop in collaboration with MPIPKS (Max Planck Institute for the Physics of Complex Systems, Dresden, Germany) using the hybrid system. The hybrid conference system comprises two screens, two projectors, a motion-tracking camera, a voice-tracking camera, and an integrated sound system. During a video conference in the PCS seminar room, the speaker delivers a presentation using materials displayed on the main screen. The motion-tracking camera automatically follows the speaker's movements, while the voice-tracking camera focuses on the audience and zooms in on the questioner. The presentation materials, together with video and audio signals of both the speaker and the audience, are transmitted to MPIPKS participants through virtual-conference software. The second screen displays both the remote MPIPKS participants and the on-site PCS audience, enabling smooth and effective real-time discussion and interaction between the two groups in the PCS seminar room.

3.5.3 Library

The library at the PCS is one of the important facilities for members, visitors, and workshop participants. Although relatively small-scale, it is having a strong impact on the operations of our center. The main role of the library lies in the management and collection of data and information resources to support all PCS members, with content decisions made by a coordinator and two community members who are appointed by group leaders. The library supports research and curriculum needs by providing pertinent materials such as research-related books and journal media, as well as scientific and non-scientific information including IBS news and policy notices. These are all offered in the library comfortable and modern facilities with journal boards, computers, blackboards, reading corners, and work desks. International e-journals are also available, following IBS guidelines. Our library stock is soon to consist of about 479 books covering the entirety of our research fields: fundamental theoretical physics, quantum optics, nonlinear dynamics, quantum chaos, quantum information, strongly correlated electronic systems, superconductivity, condensed matter physics, superfluids, ultra-cold atomic systems, bosonic and fermionic systems, mathematical physics, computational physics, soft matter physics, non-Hermitian systems, nano-electromechanical systems, device physics, and more.

The library is open during working hours from 9:00 to 18:00 and is also accessible anytime for researchers' convenience with security clearance from administration. While reference materials and journals cannot be taken out of the library, books are available for 30-day check out periods with renewals possible. Furthermore, readers may purchase particular books they require with the agreement of the community members and library organizer.

3.6 Scientific Advisory Board

To support the PCS directorship in the effort to maintain the research excellence of the Center and promote its constant growth, the PCS Scientific Advisory Board has been established. Reviewing the scientific reports prepared by the PCS every two years, the tasks of the Board include evaluation of the research achievements of the Center, analysis of its projects and collaborations, as well as preparation of a report appraising its overall performance - optimally complemented by advice on the scientific development of the Center. The first, second, third Scientific Advisory Board meetings took place in December 2016, April 2019, and June 2022.

The PCS Scientific Advisory Board consists currently of the following members:

Name	**Affiliation**
Boris Altshuler	Columbia University, USA
Yunkyu Bang	APCTP & POSTECH, Korea
David Campbell	Boston University, USA
Yong-Hoon Cho	KAIST, Korea
Byungnam Kahng	Korea Institute of Energy Technology, Korea
Dai-Sik Kim	UNIST, Korea
Naoto Nagaosa	RIKEN Center for Emergent Matter Science, Japan
Antonio Politi	University of Aberdeen, UK
Jan-Michael Rost	MPI for the Physics of Complex Systems, Germany
Lawrence Schulman	Clarkson University, USA
Peter Schwerdtfeger	Massey University, New Zealand
Mordechai Segev	Technion - Israel Institute of Technology, Israel
George Tsironis	University of Crete, Greece

3.7 Members of the Center

(as of Oct. 31, 2025)

Position	No.
Director	1
Research Fellow	10
– Junior Research Team Leader	2
– Deputy Team Leader	1
Ph.D. Student	2
Research Engineering staff	1
Administrative staff	3
– Visitor Program	2

P.: Position
D: Director
T: Tenure-track
YSF: IBS Young Scientist Fellow
RF: Research Fellow
R: Researcher / Ph.D. Student
RE: Research Engineering Staff

Name	Period	Country	P.	Research team
Alexey Andreanov	since 09/15	Russia	T	Complex Condensed Matter Systems
Olha Bahrova	07/21 - 06/24	Ukraine	R	Quantum Many-Body Interactions and Transport
Grigory Bednik	11/21 - 06/22	Russia	RF	Topological and Correlated Quantum Matter
Budhaditya Bhattacharjee	08/23 - 08/25	India	RF	Complex Condensed Matter Systems
Tilen Cadez	02/20 - 01/25	Slovenia	RF	Complex Condensed Matter Systems
Si Min Chan	04/23 - 06/23	Singapore	R	Complex Condensed Matter Systems
Yunseo Chang	since 09/25	Korea	R	Complex Condensed Matter Systems
Barbara Dietz-Pilatus	since 07/21	Germany	RF	Complex Condensed Matter Systems & Quantum Chaos in Many-Body Systems

Sergej Flach	since 12/14	Germany	D	Complex Condensed Matter Systems
Jae Ho Han	03/20 - 03/24	Korea	RF	Quantum Many-Body Interactions and Transport
Jungyun Han	03/18 - 08/22	Korea	R	Theoretical Photonics & Open Quantum Dynamics and Thermodynamics
Miguel de Jesús	since 10/24	Mexico	R	Complex Condensed Matter Systems
Beom Hyun Kim	01/23 - 11/24	Korea	RF	Topological and Correlated Quantum Matter
Hyeongseop Kim	06/24 - 08/25	Korea	RF	Superconducting Hybrid Quantum Systems
Kyoung-Min Kim	03/20 - 12/24	Korea	RF	Strongly Correlated Electronic Systems & Topological and Correlated Quantum Matter
Yeongjun Kim	since 09/20	Korea	R	Complex Condensed Matter Systems
Dogyun Ko	03/18 - 03/24	Korea	R	Light-Matter Interaction in Nanostructures
Sergei Koniakhin	since 09/21	Russia	YSF	Optics of Quantum Fluids and Nanomaterials
Pavel Kozhevin	11/24 - 03/25	Russia	R	Optics of Quantum Fluids and Nanomaterials
Aldo Lamarre	04/24 - 12/24	Canada	R	Complex Condensed Matter Systems
Gabriel Lando	12/22 - 9/25	Poland	RF	Complex Condensed Matter Systems
Hyeong Jun Lee	01/21 - 03/22	Korea	RF	Strongly Correlated Electronic Systems
Minyoung Lee	since 06/16	Korea	RE	IT Manager
Sanghoon Lee	03/21 - 02/24	Korea	R	Complex Condensed Matter Systems
Merab Malishava	09/17 - 12/22	Georgia	R	Complex Condensed Matter Systems
Arindam Mallick	03/19 - 02/23	India	RF	Complex Condensed Matter Systems
Maika Matogawa	02/25 - 07/25	Japan	R	Complex Condensed Matter Systems
Mohammad Mirzakhani	10/20 - 10/23	Iran	RF	Quantum Many-Body Interactions and Transport

Muhammad Taufiq Murtadho	03/21 - 12/22	Indonesia	R	Complex Condensed Matter Systems & Quantum Chaos in Many-Body Systems
Dillip Kumar Nandy	04/21 - 03/23	India	RF	Quantum Chaos in Many-Body Systems
Dung Xuan Nguyen	09/22 - 09/25	Vietnam	RF	Topological Quantum Matter
Aliaksei Osipau	02/24 - 05/24	Belarus	R	Optics of Quantum Fluids and Nanomaterials
Anton Parafilo	since 09/18	Ukraine	RF	Quantum Many-Body Interactions and Transport
Hee Chul Park	11/16 - 03/23	Korea	T	Quantum Many-Body Interactions and Transport
Moon Jip Park	04/21 - 03/23	Korea	RF	Topological and Correlated Quantum Matter
Sunghun Park	since 09/22	Korea	YSF	Superconducting Hybrid Quantum Systems
Aniket Patra	since 04/23	India	RF	Complex Condensed Matter Systems
Rohit Kishan Ray	02/24 - 04/25	India	RF	Complex Condensed Matter Systems
Dario Rosa	01/21 - 10/23	Italy	RF	Quantum Chaos in Many-Body Systems
Jung-Wan Ryu	since 05/20	Korea	T	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Dominik Safranek	11/20 - 07/25	Czech	RF	Quantum Chaos in Many-Body Systems & Quantum Thermodynamics and Information Theory
Ivan Savenko	02/16 - 02/23	Russia	T	Light-Matter Interaction in Nanostructures
Vahid Shaghaghi	07/21 - 12/22	Iran	R	Quantum Chaos in Many-Body Systems
Varinder Singh	12/20 - 11/23	India	RF	Quantum Chaos in Many-Body Systems
Kabyashree Sonowal	03/20 - 07/24	India	R	Light-Matter Interaction in Nanostructures

Oleg Utesov	since 06/23	Russia	RF	Complex Condensed Matter Systems & Optics of Quantum Fluids and Nanomaterials
Ihor Vakulchyk	10/16 - 02/23	Ukraine	R	Complex Condensed Matter Systems
Sonu Verma	03/22 - 12/24	India	RF	Topological and Correlated Quantum Matter
Sungjong Woo	04/18 - 03/23	Korea	RF	Quantum Many-Body Interactions and Transport
Chang-Hwan Yi	since 04/21	Korea	RF	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Weihua Zhang	01/23 - 11/23	China	R	Complex Condensed Matter Systems
Xiaodong Zhang	10/24 - 03/25	China	R	Complex Condensed Matter Systems

Chapter 4

Publications

2025

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