2019 – 2021

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.

Outlook: In 2022, the PCS aims to host four Advanced Study Groups *Deep Learning in Quantum Phase Transitions*, *Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links*, *Computational approaches to correlated systems: Applications to diverse materials*, *Incommensurately stacked atomic layers*, and organize the Dynamics Days Asia-Pacific DDAP12, an IBS-APCTP conference, and three international workshops. The Center currently has 33 members including Ph.D. students, and six research teams. The center counts 304 publications, a total of 4242 citations, and an h-index $h = 34$ on Google Scholar.

The concept of the PCS will be successful only if it is accepted by the scientific community. For this reason, the Center undertakes major efforts to ensure transparency and openness. The *Scientific Advisory Board* is an important element to promote these endeavours.

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 *Strongly Correlated Electronic Systems* led by *Ara Go*: development of numerical algorithms to study correlated electronic systems, correlation effects in materials with strong spin-orbit coupling, computational study of spectral properties in strongly correlated systems, quantum embedding theories, dynamical mean-field theory and impurity solvers.
- YSF junior research team *Theoretical Photonics* led by *Daniel Leykam*: nonlinear optics, topological phases, non-Hermitian systems, disorder and Anderson localization, flat bands, scattering, Floquet systems, photonic lattices, solitons, quantum optics.
- YSF junior research team *Nonequilibrium Quantum Thermodynamics* led by *Juzar Thingna*: dissipative quantum systems, quantum and classical thermodynamics, quantum thermodynamic machines, non-linear dynamics and thermodynamic phase transitions, heat transport in molecular junctions, open Floquet systems, symmetries and metastability in open systems, Landau-Zener open systems.
- 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.

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 2019 – 2021, 228 (onsite: 107 & online: 121) scientists visited the Center – also within special programs – with the addition of a total of 993 (onsite: 582 & online: 411) workshop participants. The worldwide COVID pandemics forced us to move heavily into online mode, and to invest into new communication technology in order to prepare for future 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 customised, thus we can accommodate practically any individual needs of our visitors. As a result, in 2019 – 2021 we hosted scientists from 31 countries, benefiting our Center from the rich diversity.

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). 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 2019, the PCS was in charge of the Focus session *Non-Hermitian systems: Symmetry and Topology* during the Korean Physical Society (KPS) Spring Meeting, and we organized the International Workshop *Physics and Applications in Nanoelectronics and Nanomechanics* in cooperation with the KIST. We hosted the first IBSPCS-KIAS International Workshop *Frustrated Magnetism*. MPK, Kunsan National University (Gunsan), and the ICTP contributed to our International Focus Workshop *Computational Approaches to Magnetic Systems*. In 2021, the PCS hosted the *IBS conference on Flatbands: symmetries, disorder, interactions and thermalization* in cooperation with the IBS CCES.

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).

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

Among other activities, two student trainees from Kharkiv (Ukraine) and Como (Italy) are currently working 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 and PCS IBS) activity coordinators Alireza Akbari (APCTP, POSTECH) and Alexei Andreanov (PCS IBS). Further network nodes and the respective node coordinators are:

- Institute of Physics, Vietnam Academy of Science and Technology, Hanoi, Vietnam (Trinh Xuan Hoang),
- School of Physics, Suranaree University of Technology, Suranari, Thailand (Worawat Meevasana),
- National Institute of Physics, University of the Philippines Diliman, Quezon City, Philippines (Cristine Villagonzalo).

The *Asian Network's* structure is further complemented by the strong ties to the ICTP Condensed Matter and Statistical Physics Section (Rosario Fazio). The network currently counts 74 participating scientists. The main activities of the network are research visits between the nodes, amounting so far to 15 visits over a total period of 37 weeks. Furthermore, the *Asian Network* holds a week-long annual school (Vietnam 2017, Thailand 2018, Philippines 2019) with 50–60 students (including the PCS students) and selected PCS team leaders among the lecturers' list. The network also supports workshops, with six conducted to date in Korea (two at the PCS). Since the start of the worldwide COVID pandemics the network activities were postponed.

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 (KAM) 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 and nonergodicity. We study the details of the impact of two-body interaction between few quantum particles on the single particle localization in real space due to disorder, and in the momentum space due to external kicks. 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. Our techniques are used to explore, predict and observe novel phases of weakly nonintegrable classical many-body dynamics beyond the horizons set by the KAM regime, and its impact on corresponding quantum many body dynamics. Main results:

- *Non-Gibbs states on a Bose-Hubbard lattice*

Phys. Rev. A 99, 023603 (2019)

- *Dynamical Glass and Ergodization Times in Classical Josephson Junction Chains*
  Phys. Rev. Lett. 122, 054102 (2019)
- *Wave packet spreading with disordered nonlinear discrete time quantum walks*
  Phys. Rev. Lett. 122, 040501 (2019)
- *Dynamical glass in weakly nonintegrable Klein-Gordon chains*
  Phys. Rev. E 100, 032217 (2019)
- *Taming two interacting particles with disorder*
  Phys. Rev. B 100, 224203 (2019)
- *Modulational Instability, Inter-Component Asymmetry, and Formation of Quantum Droplets in One-Dimensional Binary Bose Gases*
  Symmetry 12, 174 (2020)
- *Anomalous transport in a topological Wannier-Stark ladder*
  Phys. Rev. Res. 2, 023067 (2020)
- *Multifractality of correlated two-particle bound states in quasiperiodic chains*
  Phys. Rev. B 101, 174201 (2020)
- *Quench dynamics in disordered two-dimensional Gross-Pitaevskii lattices*
  Phys. Rev. A 102, 033301 (2020)
- *Density resolved wave packet spreading in disordered Gross-Pitaevskii lattices*
  SciPost Phys. Core 3, 006 (2020)
- *Bethe strings in the dynamical structure factor of the spin-1/2 Heisenberg XXX chain*
  Nuclear Physics B 960, 115175 (2020)
- *Spin-dependent two-photon Bragg scattering in the Kapitza-Dirac effect*
  Phys. Rev. A 102, 033106 (2020)
- *Bethe strings in the spin dynamical structure factor of the Mott-Hubbard phase in the one- dimensional fermionic Hubbard model*
  Phys. Rev. B 103, 045118 (2021)
- *Probing band topology using modulational instability*
  Phys. Rev. Lett. 126, 073901 (2021)
- *Thermalization in the one-dimensional Salerno model lattice*
  Phys. Rev. E 103, 032211 (2021)
- *Fragile many-body ergodicity from action diffusion*
  Phys. Rev. E 104, 014218 (2021)
- *Measuring α-FPUT cores and tails*
  Physics 3, 879 (2021)
- *Anderson localization of excitations in disordered Gross-Pitaevskii lattices*
  Phys. Rev. A 104, 053307 (2021)
- *One-particle spectral functions of the one-dimensional Fermionic Hubbard model with one fermion per site at zero and finite magnetic fields*
  Phys. Rev. B 103, 195129 (2021)

Macroscopic Degeneracies. Systems with macroscopic degeneracies are rare in nature, since the high degree of symmetry, which is needed to support them, is easily destroyed by weak perturbations. However, this is the very reason which makes macroscopic degeneracies attractive. Nowadays, manufacturing technologies can be expected to get close to realizing such symmetries - 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 may 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. Second, we study various aspects of geometric frustration. We analyze how structural and bond disorder lead to an ordered state, different from that selected by the thermal fluctuations. We further explore how constraints stemming from geometrical frustration affect the properties of a spin-glass. We study the classical Ising antiferromagnet on the pyrochlore lattice (spin-ice) with bond disorder, that exhibits a transition to a spin-glass phase. We aim at understanding how geometrical frustration modifies the critical properties of the transition from the paramagnetic to the spin-glass phase. We also study spin fragmentation in the geometrically frustrated systems. In particular, we want to show that even if a perturbation lifts the degeneracy, the fluctuations present in the system still display frustration-induced long-range correlations. Main results:

- *Necessary and sufficient conditions for flat bands in M-dimensional N-band lattices with complex-valued nearest-neighbour hopping*
  J. Phys. A: Math. Theor. 52, 02LT04 (2019)
- *Resonant frequencies and spatial correlations in frustrated arrays of Josephson type nonlinear oscillators*
  J. Phys. A: Math. Theor. 52, 105101 (2019)
- *Flat band localization and self-collimation of light in photonic crystals*
  Scientific Reports 9, 2862 (2019)
- *Universal d=1 flatband generator from compact localized states*
  Phys. Rev. B 99, 125129 (2019)
- *Casting dissipative compact states in coherent perfect absorbers*
  Phys. Rev. Res. 2, 013054 (2020)
- *Observation of quincunx-shaped and dipole-like flatband states in photonic rhombic lattices without band touching*
  APL Photonics 5, 016107 (2020)
- *Influence of different disorder types on Aharonov-Bohm caging in the diamond chain*
  Phys. Rev. A 101, 023839 (2020)
- *Many-body flatband localization*
  Phys. Rev. B Rapid Comm, 102, 041116(R) (2020)
- *Localized modes in linear and nonlinear octagonal-diamond lattices with two flat bands*
  Phys. Rev. A 102, 023532 (2020)
- *Frustration-induced highly anisotropic magnetic patterns in the classical XY model on the kagome lattice*
  Phys. Rev. B Rapid Comm. 102, 140405(R) (2020)
- *Microwave photonic crystals as an experimental realization of a combined honeycomb-kagome lattice*
  Phys. Rev. B 102, 214301 (2020)
- *Wannier-Stark flatbands in Bravais lattices*
  Phys. Rev. Res. 3, 013174 (2021)

- *Nonlinear Bloch wave dynamics in photonic Aharonov-Bohm cages*
  APL Photonics 6, 030801 (2021)
- *Flat band generator in two dimensions*
  Phys. Rev. B 103, 165116 (2021)
- *Non-Hermitian flat band generator in one dimension*
  Phys. Rev. B 104, 035115 (2021)
- *Nonlinear caging in all-bands-flat lattices*
  Phys. Rev. B 104, 085131 (2021)
- *Quantum caging in all-bands-flat lattices*
  Phys. Rev. B 104, 085132 (2021)
- *Heat percolation in many-body flatband localizing systems*
  Phys. Rev. B 104, 144207 (2021)
- *Metal-insulator transition in infinitesimally weakly disordered flat bands*
  Phys. Rev. B 104, L180201 (2021)

Unitary Map Toolbox. To address a growing number of hard fundamental computational tasks, we use a novel unitary map toolbox – e.g. discrete-time quantum walks (DTQW), unitary circuits, or other versions. Their highly efficient coding implementation is the key to address suitable hard computational problems with Hamiltonian dynamics, and extend beyond Hamiltonian computational limits. At the same time the unitary maps can easily incorporate disorder, nonlinearities, and many-body interactions. 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 used two-body interactions to study the localization length increase for two interacting particles in random potentials. Additional Bohr-Sommerfeld quantization of nonlinear extensions allowed to observe the gradual halt of subdiffusive wavepacket spreading through an extended logarithmic spreading regime. Recently we used nonlinear unitary maps to classify many-body thermalization of weakly nonintegrable systems by computing the entire Lyapunov spectrum and by analyzing its scaling properties. Main results:

- *Wave Packet Spreading with Disordered Nonlinear Discrete-Time Quantum Walks*
  Phys. Rev. Lett. 122, 040501 (2019)
- *Spectral magnetization ratchets with discrete-time quantum walks*
  Phys. Rev. A 101, 032119 (2020)
- *Floquet Anderson localization of two interacting discrete time quantum walks*
  Phys. Rev. B 101, 144201 (2020)
- *Topological delocalization in the completely disordered two-dimensional quantum walk*
  Phys. Rev. B 102, 224202 (2020)
- *Time molecules with periodically driven interacting qubits*
  Quantum Sci. Technol. 6, 035012 (2021)
- *Logarithmic expansion of many-body wavepackets 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)

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:

- *Statistical properties of chaotic microcavities in small and large opening cases*
  Chaos 29, 043123 (2019)
- *Optimization of conformal whispering gallery modes in limacon-shaped transformation cavities*
  Scientific Reports 9, 8506 (2019)
- *Casting dissipative compact states in coherent perfect absorbers*
  Phys. Rev. R 2, 013054 (2020)
- *Is there a Floquet Lindbladian?*
  Phys. Rev. B 101, 100301(R) (2020)
- *Whispering gallery modes in triple microdisks of triangular configurations*
  J. Opt. Soc. Am. B 37, 2382 (2020)
- *Colloquium: Statistical mechanics and thermodynamics at strong coupling: quantum and classical*
  Rev. Mod. Phys. 92 041002 (2020)
- *Probing bulk topological invariants using leaky photonic lattices*
  Nat. Phys. 17, 632 (2021)
- *Transformation cavities with a narrow refractive index profile*
  Optics Letters 46, 1900 (2021)
- *Salient role of the non-Hermitian coupling for optimizing conditions in multiple maximizations of inter-cavity light transfer*
  Opt. Express 29, 19998 (2021)
- *Raleigh scatterer-induced steady exceptional points of stable-island modes in a deformed optical microdisk*
  Opt. Lett. 46, 2980 (2021)
- *Non-Hermitian flat band generator in one dimension*
  Phys. Rev. B 104, 035115 (2021)
- *Stochastic dynamics of inertial-like Stuart-Landau dimer*
  New J. Phys. 23, 105005 (2021)

More. Various other research activities enrich and cross-fertilize the work of the team. These include pertinent questions of the scattering impact of surface fractals, quantum thermodynamics, machine learning and neural networks, the dynamics of superfluid Fermi gases, metal-insulator transitions with Luttinger liquids, and superconducting qubit studies, among others. Main results:

- *Modulation instability associated nonlinear dynamics of spin-orbit coupled Bose-Einstein condensates*
  J. Phys. B.: At. Mol. Opt. Phys. 52, 045301 (2019)
- *Electromagnetic wave propagation through an array of superconducting qubits: manifestations of nonequilibrium steady states of qubits*
  Phys. Rev. A 100, 023844 (2019)
- *Two-tone spectroscopy of a SQUID metamaterial in the nonlinear regime*
  Phys. Rev. Res. 1, 033096 (2019)

- *Locally optimal 2-periodic sphere packings*
  Discrete Computational Geometry 63, 182 (2020)
- *Low-density expansions for the homogeneous dipolar Bose gas at zero temperature*
  Phys. Rev. A 100, 063631 (2019)
- *Probing an excited-state quantum phase transition in a quantum many-body system via an out-of-time-order correlator*
  Phys. Rev. A 100, 062113 (2019)
- *Interplay of vibration and Coulomb effects in transport of spin-polarized electrons in a single- molecule transistor*
  Superlattices and Microstructures 137, 106356 (2020)
- *Modulational instability, inter-component asymmetry, and formation of quantum droplets in one- dimensional binary Bose-gases*
  Symmetry 12, 174 (2020)
- *Signatures of quantum chaos in the dynamics of bipartite fluctuations*
  Physica A 554, 124321 (2020)
- *Heterogeneous TRP channel model of a chordotonal neuron might explain Drosophila hearing*
  J. Korean Phys. Soc. 76, 118 (2020)
- *Identification of chimera using machine learning*
  Chaos 30, 063128 (2020)
- *Explosive synchronization in multilayer dynamically dissimilar networks*
  J. Comp. Science 46, 101177 (2020)
- *Deep learning of chaos classification*
  Machine Learning: Science and Technology 1, 045019 (2020)
- *Investigating mitonuclear genetic interactions through machine learning: a case study on cold adaptation genes in human populations from different European climate regions*
  Frontiers in Physiology 11, 575968 (2020)
- *Interlayer Hebbian plasticity induces first-order transition in multiplex networks*
  New J. Phys. 22, 122001 (2020)
- *Giant persistent photoconductivity in monolayer MoS2 field-effect transistors*
  npj 2D Materials and Applications 5, 15 (2021)
- *Analysis of human mitochondrial genome co-occurrence networks of Asian population at varying altitudes*
  Scientific Reports 11, 133 (2021)
- *Multifractal analysis of eigenvectors of small-world networks*
  Chaos, Solitons Fractals 144, 110745 (2021)
- *Impact of modular mitochondrial epistatic interactions on the evolution of human subpopulations*
  Mitochondrion 58, 111 (2021)
- *Fast frequency discrimination and phoneme recognition using a biomimetic membrane coupled to a neural network*
  Journal of the Korean Physical Society 78, 373 (2021)
- *Explosive synchronization in inter-layer phase-shifted Kuramoto oscillators on multiplex networks*
  Chaos 31, 041103 (2021)

- *Machine learning assisted chimera and solitary states in networks*
  Frontiers in Physics 9, 513969 (2021)

Perspectives

The division and the team were established in January 2015, with the arrival of Sergej Flach. However, in reality, the scientific activities started with the hiring of the first team members in May 2015. 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 unitary circuits and thermalization of weakly nonintegrable many body systems. 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 making the fields of quantum information and machine learning an integral part of our work. 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 chiral spin groundstates (KAIST, Daejeon), many-body localization and quantum glasses (APCTP, Pohang), and non-Hermitian optics (Pusan National University, Busan; KAIST, Daejeon; Kyungpook National University, Daegu; NIMS, Daejeon).

International cooperations include geometric frustration (OIST, Japan; STFC, UK), sphere packing (Santa Fe Institute, USA), non-Hermitian physics (National Technical University of Athens, Greece; University of Patras, Greece; Columbia University, USA; UNAM, Mexico), flat bands (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), 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.

- *A strain-engineered graphene qubit in a nanobubble*
  reviewing in npj Quantum Information.
- *Machine learning approach to recognition of a nanobubble in graphene*
  Appl. Phys. Lett. (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 Cat states generated by a dc voltage-driven Cooper pair box qubit*
  reviewing in npj Quantum Information.
- *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.

- *Strongly Coupled Photonic Moire Superlattices*
  reviewing in Light: Science & Applications.
- *Topological edge states in bowtie ladders*
  Physica E, PHYSE114941 (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. 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 2019, the team consisted of five members: the junior research team leader, *Ivan Savenko*, Research Fellows, *Kristian Villegas* and *Sukjin Yoon*, and two Ph.D. students, *Meng Sun* and *Dogyun Ko.* In 2019 Ms. Kabyashree Sonowal joined the team as a PhD student.

- With *Meng Sun,* we discovered a new mechanism of superconductivity in transition metal dichalcogenides and graphene in the vicinity of a Bose-Einstein condensate. The theory has been built for the cases of weak and strong coupling regimes.
  – 2D Materials 8, 031004 as a Letter (2021)
  – Phys. Rev. Research 3 (3), 033166 (2021)
- We performed a joint research with our experimental colleagues from Germany on coherent topological exciton-polariton laser.
  – ACS Photonics 8(5) 1377 (2021)
- We developed the first theory of the Photoinduced Valley Hall effect.
  – Phys. Rev. B 103, 035434 (2021)
- We proposed a method, which allows optical monitoring of low-dimensional superconductors in the fluctuating regime. This technique works close to the plasmon resonance frequency of the material and at temperatures when the superconducting fluctuations

appear.
– Phys. Rev. Letters 124, 207002 (2020)

- We proposed an optical transistor for amplification of radiation in a broadband terahertz domain. This device is based on novel two-dimensional quantum materials.
  – Phys. Rev. Letters 124, 087701 (2020)
- We discovered two fundamental effect: Valley Acoustoelectric Effect and Valley Acoustoelectric Hall Effect in novel two-dimensional quantum materials. These effects arise in such material as transition metal dichalcogenide monolayers residing on a piezoelectric substrate. The essence of this effect lies in the emergence of a drag electric current (and a spin current) due to a propagating surface acoustic wave in the system.
  – Phys. Rev. Letters 122, 256801 (2019)
- With my (now graduated) PhD student, Meng Sun, and a Postdoctoral Fellow, Dr. Kristian Villegas, we discovered an unconventional mechanism of electron scattering in graphene in hybrid Bose-Fermi systems. We studied energy-dependent electron relaxation time, accounting for the processes of emission and absorption of a Bogoliubov excitation (a bogolon). Then using the Bloch-Gruneisen approach, we found the finite-temperature resistivity of graphene and showed its principal behavior in the limits of low and high temperatures.
  – Phys. Rev. Letters 123, 095301 (2019)

Future Prospects

From the general perspective, we plan to *hire more people* in the group (Ph.D. students and postdoctoral researchers). Beside focusing on the scientific work, we plan to participate in several conferences (in particular, PLMCN and META). Moreover, we are planning to continue organizing the workshop “International Workshop on exciton-polaritons in emerging materials” which was put on hold due to the Corona situation.

The *scientific plans* include:

- With *Dogyun Ko* we are working on topological physics in the exciton-polariton microcavities under incoherent excitation. We are also working on the photon drag effect in systems of different dimensionality.
- With *Kabyashree Sonowal* we are working on Rayleigh acoustic waves in 2D materials and their influence on electronic transport.
- Other plan is the following. We will elucidate the role of collective excitations in the processes of nonlinear interaction of electromagnetic waves with low-dimensional superconductors. In addition to quasiparticle excitations, a superconducting electron gas in 3D systems has a collective mode, which represents oscillations of the order parameter. The long-range Coulomb interaction ‘pushes’ the collective mode into the region of the plasma frequencies of the 3D electron gas. However, the plasma modes do not play a significant role, since the plasma frequency of the 3D electron gas exceeds the magnitude of the superconducting gap. A completely different situation can be expected in 2D electron gas, even in the presence of Coulomb forces. Here, collective modes will make a significant contribution to the absorption of light beyond the threshold. Graduate students can be involved in this project for analytical derivations and numerical modeling.
- Furthermore, we will put the superconductor in a hybrid setup, where the Cooper pairs interact with electrons in a 2DEG in a normal metal or graphene, and find the eigen modes of the system and study their interaction with an incident light. We will calculate the spectrum of electric current in the system and the photon drag

current, when the light falls on the surface of the system with a finite momentum. We plan to study the effects of the second-order in the amplitude of the electromagnetic field, which includes the second harmonic generation being an effective tool for the frequency conversion of electromagnetic radiation. We will calculate the second-order gauge-invariant response both above and below the Tc, taking into account scattering by impurities. This project also implies involvement of graduate students.

- Further we will switch from optical to acoustic drag and study valley acoustoelectric Hall effect in 2D materials (TMD monolayers) and superconductors, residing on various substrates. We will calculate the drag electric current and a spin current due to propagating surface acoustic waves (Rayleigh, Gulyaev-Blushtein, and Love waves) along the structure. In particular, we will study the effects of the trigonal warping of the electron dispersion and the Berry phase, which Bloch electrons acquire traveling along the crystal. Furthermore, we will build a theory of acoustoelectronic transport in external fields, both magnetic and pseudomagnetic due to static inhomogeneous deformation, addressing paramagnetic acoustic spin and cyclotron resonances, and the Weiss oscillations.
- We will consider topological superconductors, extending the optical techniques developed in projects 1, 2 on these systems. They are especially difficult to treat (especially analytically) due to the difference between the bulk and surface properties. We will consider a system consisting of parallel layers of graphene and a topological superconductor, exposed to an electromagnetic field incident at some angle at the surface and linearly polarized along the x-z plane (p-polarisation). Between graphene layer and superconductor there is a gate voltage, which controls its chemical potential. The electrons in graphene interact via the Coulomb interaction, the electrons between the two layers are also Coulomb-coupled. The eigenmodes of the system will be found from the eigenvalue equation. Next we will find the polarization operators for both the layers. Then we will find the electromagnetic power absorption spectrum. It will allow us to find the differences in optical response in the cases of conventional and topological superconductors. We will use numerical integrations and solution of differential equations. Graduate and undergraduate students will participate in analytical modeling and simulations.

1.6.4 Strongly Correlated Electronic Systems
Team Leader: Ara Go

The interactions between components of a system may result in emergent properties that are surprisingly different from those of individual parts. We investigate the various emergent phenomena induced by strong interactions. Metal insulator transitions, fractionalized excitations, and topological transitions are good examples of these emergent phenomena. The scope of these phenomena is very wide, and we have focused on the electronic systems such as transition metal compounds and quantum spin systems. We actively develop numerical algorithms and exploit it as a tool to study the strongly correlated electronic systems. The team consists of three members, Hyeong Jun Lee, Kyoung-Min Kim (jointly with the team "Topological and Correlated Quantum Matter"), Ki Hoon Lee (PCS Associate), and the team leader – Ara Go.

Research Topics

Spin-orbit coupled transition metal compounds Recently, the spin-orbit coupling has attracted the reinforced attention of many researchers, because it is a key ingredient of a topologically insulator. The spin orbit-coupling contributed to the discovery of a new class of materials which initiated an intensive research activities. On the other hand, in computational context, it makes computational simulations more difficult, since spin and orbital momentum no longer function as good quantum numbers in the presence of spin-orbit coupling. Then, dimension of an effective Hamiltonian increases and computational costs also grow.

The local Coulomb interaction enables novel phases out of the systems. Essentially new types of quasiparticles and collective excitations can be stabilized by the interactions. However, the interesting complexity accompanies additional computational difficulties. Many variants of transition metal compounds, cuprates, ruthenates, and iridates, have the spin-orbit coupling and the local Coulomb interaction of non-negligible size. Special care must be taken to apply powerful computational tools, density functional theory, and dynamic average field theory to such systems. We develop and implement new algorithms to solve the complicated problems to search the novel phase diagram. By exploiting these method, we found the interplay between the spin-orbit coupling and the local interactions arises peculiar multiplet excitations out of many-body quantum states.

Hund's metal In the crystal systems, the multiplet population may vary depending on the interaction strengths as well as the allowed hopping between sites. A good example is a Mott-Hubbard metal-insulator transition, which is driven by the local Hubbard interaction. The Hubbard interaction prevents multiplets with doubly occupied orbitals by opposite spins and it results in suppression of itinerant electrons. The Mott insulator is based on many-body physics and it cannot be explained by any single-particle picture. It demands an appropriate framework, such as the dynamical mean-field theory (DMFT), to deal with the many-body correlation.

The DMFT has proven its power by reproducing a phase diagram of generic Mott-Hubbard transition including a correlated metallic phase. Recent development of the technique opened a new direction of research – the Hund's metal. The local Coulomb interaction in a multi-orbital system has two distinct energy scales, the Hubbard interaction U and the Hund coupling J. The Hubbard interaction affects energy costs to change the number of electrons in the system. For a given chemical potential, the optimal number is determined by the Hubbard term. The Hund's coupling, on the other hand, controls the distribution of the electrons in the orbitals. It tunes the probability distribution of local multiplets the same number of electrons. Depending on circumstances, the Hund's coupling yields a peculiar metallic phase, characterized by a enhanced long-time spin correlator and a reduced quasiparticle weight. We investigate how this Hund's metallicity interplays with other degrees of freedom in a crystal systems, aiming at a new phase of matter.

Kitaev quantum spin liquids The quantum spin liquids (QSLs) is a phase of matter which does not have any long-range magnetic ordering at zero temperature, hosting long-range quantum entanglement. The well-known hallmark of the QSL is the fractionalized excitations, for instance, spinons. The Kitaev honeycomb model is exactly solvable, with the Z_2 QSL ground state. Since the theoretical recipe was proposed in the presence of the strong spin-orbit coupling, there have been extensive works to find the materials. We investigate the Kitaev systems by means of more rigorous numerical schemes, such as the exact diagonalization and thermal pure quantum state formalism for quantum spin models.

Among the many candidate materials, the layered honeycomb material α-$RuCl_3$ is turned out to be a QSL. The half-quantized value of the thermal Hall conductivity κ_{xy}/T, which is a direct evidence of Majorana edge mode, has been observed in α-$RuCl_3$ under an external magnetic field. Near the zero temperature, the κ_{xy}/T shows upturn as the temperature increases, while the original Kitaev model is supposed to give downturn. We found that the upturn can be understood by a certain combination of Chern numbers of Majorana edge modes and proposed a spin model realizing the peculiar structure. The parton mean-field solution reproduces the critical fan shape of the experimental phase diagram. It immediately calls a series of works to verify the reliability of the solution under various circumstances: temperature, magnetic fields, pressure, and so on.

On the other direction, theoretical study on the Kitaev system can provide a method to identify the Kitaev QSL in experiments. While the aforementioned thermal Hall conductivity is an indisputable evidence of a Kitaev spin liquid, its experimental realization is not simple. The experiment takes a long time and also it requires a fine heat control during the measurement. We computationally test the responses of the Kitaev spin liquid under the various environment and suggest a way to experimental confirmation of the QSL.

Collaborations

We work with many domestic and international collaborators, including experimentalists, computational experts, and field theorists:

- Spin-orbit coupled transition metal compounds and Hund's metal
  – IBS-CCES, Korea (Dr. Choong Hyun Kim, Prof. Changyoung Kim, Prof. Tae Won Noh)
  – KAIST, Korea (Prof. Myung Joon Han)
  – UNIST, Korea (Prof. Hosub Jin) – SNU, Korea (Prof. Je-Geun Park) – Universität zu Köln, Germany (Prof. Daniel I. Khomskii)
- Kitaev quantum spin liquid
  – KAIST, Korea (Prof. Eun Gook Moon) – Tokyo University, Japan (Prof. Takasada Shibauchi)
  – University of Toronto, USA (Prof. Yong Baek Kim)

Future Perspectives

We pursue the discovery and understanding of new novel states of matter driven by interaction. Since this is fundamentally a many-body phenomenon, the contribution of computational approach is essential. By developing and applying efficient numerical algorithms, we will contribute to unveil the nature of the correlated systems. The original junior research team work faded out with the move of the team leader to a faculty position, and with the move of team members to new positions outside IBS. The associate status of the team leader and one former member allowed to smoothly continue and transform the activities.

1.6.5 Theoretical Photonics
Team Leader: Daniel Leykam

Research Topics

Nonlinear topological photonics. At the linear, non-interacting level, photonic topological systems behave similar to their electronic condensed matter counterparts. Strong differences emerge in the nonlinear and quantum regimes, leading to novel phenomena including solitons, bifurcations, and chaos. Main results:

- *Topological edge states and gap solitons in the nonlinear Dirac model*
  Laser & Photonics Reviews 13, 1900223 (2019)
- *Third-harmonic generation in photonic topological metasurfaces*

Physical Review Letters 123, 103901 (2019)

- *Edge mode bifurcations of two-dimensional topological lasers*
  Optics Letters 45, 3673 (2020)
- *Nontrivial coupling of light into a defect: the interplay of nonlinearity and topology*
  Light: Science & Applications 9, 147 (2020)

Photonic flatbands. Dispersionless flatbands attract increasing interest in photonics, with applications including the design of localized modes in waveguide lattices and slow light in photonic crystals. We have studied theoretically and experimentally signatures of different classes of flatbands, including the emergence of protected line and edge modes and their robustness to disorder and nonlinear interactions. Main results:

- *Nonlinear symmetry breaking of Aharonov-Bohm cages*
  Physical Review A 99, 013826 (2019)
- *Influence of different disorder types on Aharonov-Bohm caging in the diamond chain*
  Physical Review A 101, 023839 (2020)
- *Direct observation of flatband loop states arising from nontrivial real-space topology*
  Physical Review Letters 124, 183901 (2020)
- *Flatband line states in photonic super-honeycomb lattices*
  Advanced Optical Materials 8, 1902174 (2020)

Signatures of bulk topological invariants. In topological photonics it is the robust edge modes appearing at the edges of topologically nontrivial systems that have attracted the most interest, owing to their potential applications as disorder-robust optical waveguides. More recently, the discovery of protected modes localized to bulk defects and generalizations of the bulk-edge correspondence have sparked interest in robust topological phenomena in bulk media. We have studied ways in which topological protection manifests in the bulk of topological photonic systems, including how to measure bulk topological invariants in photonic systems. Main results:

- *Valley vortex states and degeneracy lifting via photonic higher-band excitation*
  Physical Review Letters 122, 123903 (2019)
- *Universal momentum-to-real-space mapping of topological singularities*
  Nature Communications 11, 1 (2020)
- *Probing bulk topological invariants using leaky photonic lattices*
  Nature Physics 17, 632 (2021)
- *Probing band topology using modulational instability*
  Physical Review Letters 126, 073901 (2021)

Perspectives

The Junior Research team had been established in 2017 with the arrival of Daniel Leykam as a Young Scientist Fellow. From 2019 the team included two Research Fellows, Pramod Padmanabhan and Sinan Gündoğdu, as well as a Ph.D. student, JungYun Han. In June 2019 we hosted an International Workshop, *Recent Advances in Topological Photonics*, which attracted 72 invited speakers and participants representing 11 countries. During 2020 we hosted a long term visitor, Dr. Aleksandra Maluckov. In August 2020 Daniel and Pramod left IBS to take up positions at the National University of Singapore and Sungkyunkwan University, respectively, while JungYun moved to the Nonequilibrium Quantum Thermodynamics team. The activities of the group concluded in June 2021 with the departure of Sinan to take up a Research Fellow position at the Humboldt University of Berlin. Collaboration between our team alumni and other teams at PCS continues.

Collaborations

Within IBS we collaborated with the Nonequilibrium Quantum Thermodynamics, Light-Matter Interaction in Nanostructures, and Complex Condensed Matter Systems teams at PCS, and with Jun Won Rhim at the Center for Correlated Electron Systems.

International collaborations included:

- Zhigang Chen (Nankai University, China) – optically-induced photonic lattices,
- Mohammad Hafezi (NIST / University of Maryland, USA) – silicon photonics,
- Yuri Kivshar (Australian National University, Australia) – nonlinear metasurfaces,
- Daria Smirnova (Russian Academy of Sciences, Russia) – nonlinear photonics,
- Aleksandra Maluckov (University of Belgrade, Serbia) – photonic flatbands,
- Yidong Chong (Nanyang Technological University, Singapore) – topological photonics,
- Franco Nori (RIKEN, Japan) – topological photonics,
- Luqi Yuan (Shanghai Jiaotong University, China) – resonator lattices,

with the first three being experimental collaborations.

1.6.6 Nonequilibrium Quantum Thermodynamics
Team Leader: Juzar Thingna

Research Topics

Quantum synchronization. To study quantum synchronization we explored three different directions: i) We developed the quantum thermodynamics framework of an open discrete PT-symmetric dimer model that exhibits synchronization. The model showed a phase transition from coherent to incoherent limit cycle regimes which were reflected in the thermodynamic observables. Our model is the first hybrid non-Hermitian Lindblad model to display quantum synchronization. ii) We investigate the interplay between degeneracies, interference, and quantum synchronization by studying a four-level system connected to two thermal reservoirs depicting a laser heat engine. We were able to map this model to that of oscillators and analyze the physics as that of competition between entrainment and coupling between the oscillators. One of our main results shows that when the interference from the bath is destructive, the coupling between the oscillators dominates which causes power of the engine to be no longer bounded by the synchronization measure. In the opposite regime of constructive interference, the entrainment dominates over the coupling and the universal bounds on power by synchronization measure is recovered. Our analytic results are corroborated with numerical experiments that allow us to investigate N oscillator model and study the interplay between the coupling and entrainment in presence of collective effects. iii) Lastly, we have looked at non-Kerr type photonic interactions and shown that synchronization can help cool the quantum system whereas non-synchronous behavior always leads to heating. All these works, have been home-grown efforts to study the thermodynamics of quantum synchronization. Main results:

- R. Manyil and J. Thingna, "Quantum transport in non-Hermitian open systems," (in preparation).
- T. Murtadho, S. Vinjanampathy, and J. Thingna, "Entrainment Instability in Quantum Degenerate Laser Heat Engines," (in preparation).
- J.-Y. Han, D. Leykam, D. G. Angelakis, and J. Thingna, "Quantum transient heat transport in hyper-parametric oscillator," Phys. Rev. A **104**, 052220 (2021).

Classical synchronization. We introduced a new minimal model of classical synchronization known as the inertial Stuart-Landau dimer, that displays coexistence of coherent and incoherent limit cycles (bistability). Such phases are not observed in the standard model. Using linear stability analysis we were able to explain the boundaries of the various phases using semi-analytics. We were able to connect the inertial Stuart-Landau dimer to a system of interacting particles in a magnetic field which would allow experimentalists to replicate our model and validate our theoretical claims. The physical description of the particles in a magnetic field allowed us to rigorously define the thermodynamic observables like heat and work and we were able to furthermore connect to the mathematical definitions found in the literature. Main results:

- J.-W. Ryu, A. Lazarescu, R. Marathe, and J. Thingna, “Stochastic thermodynamics of inertial Stuart-Landau dimer,” New J. Phys. **23**, 105005 (2021).

Open quantum symmetries. We extensively explored the role of open system symmetries in the nonequilibrium thermodynamics of quantum systems. We showed that in presence of open quantum system symmetries, the direction of a magnetic field can be used a critical tool to control the flow of heat and particles. We analytically proved that in presence of open system symmetries the system can have multiple steady states, and showed a universal algorithm to obtain all the nonequilibrium steady states of such a open quantum system. Lastly, we disproved a widely-held belief that open system symmetries that lead to decoherence free subspaces could be an essential ingredient to build quantum batteries. We showed via a rigorous thermodynamic analysis that quantum batteries that rely on open system symmetries turn out to be dissipate energy to the surroundings thus being ‘leaky’ batteries. Main results:

- J. Thingna, D. Manzano, and J. Cao, “Magnetic field induced symmetry breaking in nonequilibrium quantum networks,” New J. Phys. **22**, 083026 (2020).
- J. Thingna and D. Manzano, ”Degenerated Liouvillians and steady-state reduced density matrices, ” Chaos **31**, 073114 (2021).
- Á. Tejero, J. Thingna, and D. Manzano, ”Comment on: ”Loss-free excitonic quantum battery”,” J. Phys. Chem. C **125**, 7518 (2021).

Driven quantum systems. We extensively explored Floquet dynamics of game theoretic classical model were able to show how metastable states emerge. Our main theoretical results were applied to further our understanding of population dynamics of a species and we showed how competition within the species can give rise to long lived mutant states. On the quantum side, we developed a Floquet engineering approach to design quantum materials utilizing a driving field exploiting the Lie-algebraic structure of Hamiltonians. Our key achievement was to develop an exact formulation that helps us design the shape of the driving which is valid for any driving frequency. We designed paradigmatic flat-band system known as the cross-stitch ladder using our method which utilized local driving on a simple site Hamiltonian. We now plan to realize topological flat-band models using our scheme. The periodic driving was also used to envisage a counter-intuitive quantum pump that was highly efficient at large dissipation. Main results:

- S. Denisov, O. Vershinina, J. Thingna, P. Hänggi, and M. Ivanchenko, ”Quasi-stationary states of game-driven systems: A dynamical approach,” Chaos **30**, 123145 (2020).
- J. N. Bandyopadhyay and J. Thingna, “Floquet engineering of Lie algebraic quantum systems,” Phys. Rev. B (Letters) **105**, L020301 (2022).
- E. C. Cuansing, J.-S. Wang, and J. Thingna, ”Nonadiabatic particle and energy pump at strong system-reservoir coupling,” arXiv:2003.04589 (2020).

Quantum measurements. We first introduced a novel scheme to measure a sum of observables with a minimum backaction on the quantum system. The scheme outperformed other commonly used schemes such as repeated measurements and we were able to analytically prove that our schemes performance scales with N (N being the number of measurements performed). We then used this new measurement scheme to boost the performance of Otto heat engines and study the influence of measurements on the performance of heat engines. Our main finding is that normally coherence is eliminated due to the measurement protocol but our scheme preserves coherence and this enhances the engine in all metrics like reliability, efficiency, and power output. We also used our scheme to explore the effects on observational entropy and were able to show how our method can be used to predict the state of the system, being an alternative to standard quantum tomography protocols. Lastly, we explored how the measurement of a quantum battery affects its charging process when charged by an Otto engine. We showed that measuring the battery regularly destroys all coherences causing the battery to charge slower and store less useful energy. Our predictions will help design appropriate charging protocols for quantum batteries. Main results:

- J. Thingna and P. Talkner, "Quantum measurement of sums," Phys. Rev. A **102**, 012213 (2020).

- J. Son, P. Talkner, and J. Thingna, "Monitoring quantum Otto engines," Phys. Rev. X Quantum **2**, 040328 (2021).

- D. Ŝafránek and J. Thingna, "Quantifying Information Extraction using Generalized Quantum Measurements," (in preparation).

- J. Son, P. Talkner, and J. Thingna, "Charging quantum batteries via Otto engines," (in preparation).

Perspectives

The Young Scientist Fellow team was established in February 2019, with Juzar Thingna. The team recruited its first member, Rohith Manayil, in August 2019 followed by Jayendra Bandyopadhyay in February 2020. Taufiq Murtadho joined the team in March 2020 followed by Dominik D. Ŝafránek and Varinder Singh in November 2020. The research team broadly worked on nonequilibrium quantum dissipative systems and quantum thermodynamics with a focus on the themes listed above. We searched for quantum phenomena that would help enhance device performance and provide a quantum advantage using analytic and state-of-the-art high performance computing tools. The team activities faded out with the leave of the team leader to a post in the USA. The associate status of the team leader allowed for a smooth continuation of some projects. Team members joined other PCS teams and especially a new team installed and led by Dario Rosa (see below).

Cooperations

Within the PCS, we collaborated with all junior research teams.

International cooperation includes quantum synchronization (NUS, Singapore and IIT Bombay, India), classical synchronization (UC Louvain, Belgium and IIT Delhi, India), open quantum symmetries (University of Granada, Spain and MIT, USA), driven quantum systems (University of Augsburg, Germany; University of Philippines Los Baños, Philippines; NUS, Singapore; BITS Pilani, India; Oslo Metropolitan University, Norway; and Lobachevsky University, Russia), and quantum measurements (SNU, South Korea and University of Augsburg, Germany).

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

Research Topics

The common theme in our research is to understand how quantum chaos (or its absence) affects the physics of quantum many-body systems. With this in mind, here are the main research lines that we pursue and that we are going to explore in the near future.

Towards a unified notion of quantum chaos. Historically, quantum chaos has been described via the so-called Bohighas-Giannoni-Schmit conjecture, which in a nutshell says 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. Although both these definitions are appealing and reasonable, it is not yet clear whether they are fully equivalent when dealing with many-body systems. One of our main long term goals is to understand in details how they are related and how to find a unified notion quantum chaos. Along this line, we recently uncovered a two-steps structure in scrambling dynamics: operator growth and the new phenomenon of *operator delocalization.* The latter is mostly unrelated to the spectral properties of the many-body Hamiltonian while it is highly affected by its degree of locality.

Main results:

- Joonho Kim, Jan Olle, Jeff Murugan and Dario Rosa, *Operator Delocalization in Quantum Networks*, to appear in *Phys. Rev. A.*
- Matteo Carrega, Joonho Kim and Dario Rosa, *Unveiling Operator Growth Using Spin Correlation Functions*, *Entropy* 23 (2021) 5, 587.

How to escape from quantum chaos: many-body localization. Generic quantum many-body systems are chaotic. Hence, it is interesting to look for ways to escape from quantum chaos. The most well-known examples are integrable systems. Unfortunately, integrable systems are typically very *fragile*, and a very small perturbation is often enough to fully destroy integrability and restore quantum chaos. More recently, a *robust* way to escape from quantum chaos has emerged, under the name of many-body localization. In many-body localized systems, the presence of disorder prevents the system from diffusion and quantum chaos is suppressed. It is still under debate whether the many-body localization mechanism survives in the thermodynamic limit.

Motivated by these controversial results, one of the main questions we are addressing is the fate of many-body localization in the thermodynamic limit. To this purpose, we are looking for many-body localized systems based on deformations of the so-called Sachdev-Ye-Kitaev model, a strongly chaotic model which nevertheless can be solved in the thermodynamic limit. Thanks to this solvability property, it can be considered as a perfect playground to test how finite scale scaling analysis are reliable in describing the thermodynamic limit of putative MBL systems. In parallel we are also investigating the behavior in the thermodynamic limit of a new diagnostic of quantum chaos: the adiabatic gauge potentials. Once again, we are testing this new observable in deformations of the SYK model as well as in the famous quasi-periodic Aubry-André model.

Another line of research we are pursuing is the use of machine learning methods to detect the ETH/MBL transition in finite size systems. In recent years, machine learning algorithms, and in particular neural network architectures, have been heavily tested as tools to detect various kind of phase transitions in many-body systems. However, all the studies at disposal in the literature are based on supervised learning methods in which both the training data and the validation data are coming from the *same* physical model. As a matter of fact, such studies do not address the important question of the extent to which a neural network, once trained on a given *well-known* model can be used to investigate a different model *without further re-training.* This point represents a crucial step to promote neural networks from the status of tools to better investigate models already well-studied to the status of a tool to actually investigate new and unknown models. We have recently showed that, once trained on the prototypical example of the disordered Heisenberg model, a neural network is able to correctly identify the ETH-MBL transition in new models, differing by the connectivity of the underline graph, without further re-training.

Main results:

- Dillip Nandy, Alexei Andreanov, Tilen Cadez, Barbara Dietz and Dario Rosa, *in preparation.*
- Cameron Beetar, Jeff Murugan and Dario Rosa, *Neural Networks as Universal Probes of Many-Body Localization in Quantum Graphs*, under consideration in *Phys. Rev. Lett.*

How to escape from quantum chaos: quantum many-body scars. Much more recently a new and intriguing way to escape from quantum chaos has been described under the name of *quantum many-body scars.* Simply put, this term refers to particular quantum many-body systems where, although the vast majority of the spectrum is chaotic, very few, sporadic and isolated, states show strong departures from quantum chaos predictions. These states are referred as scarred states and it has been shown that their presence strongly affect some dynamical features of the underlying system. A common theme occurring on systems exhibiting many-body scarred states is the phenomenon of *Hilbert space fragmentation*, *i.e.* the property of the Hilbert space to split in a multitude of chambers separated from each other. Such a fragmentation is not usually associated with the presence of distinct symmetry sectors.

We are currently interested in studying the stability of the many-body scarred states against perturbations, with particular emphasis on perturbations breaking the fragmentation of the underlying Hilbert space. Another line of research we are currently pursuing is in finding explicit examples, based on the so-called Maldacena and Qi SYK-model, of the newly introduced *rainbow many-body scars* and to understand the implications on the dynamics of such states.

Quantum many-body batteries 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 which is able to 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 be then discharged by bringing it back to a low energy state. Several figures of merit can be then 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 in 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.

We have been able to show, that both these goals can be achieved by means of strongly chaotic quench Hamiltonians, with once again the Sachdev-Ye-Kitaev model being a perfect candidate, and we are currently working on understanding all the implications of these observations. Among the results we already achieved, we have been able to find a tight bound on the maximal charging power that a generic quantum many-body battery can reach, and we uncovered an intriguing and new connection between the charging power of a given quantum battery and the operator delocalization properties of the corresponding quench Hamiltonian.

On another line of research, we are studying explicit physical setups to realize models of quantum batteries. On this respect, we are currently studying how micromasers can be used as quantum batteries. Somehow surprisingly, we are finding that micromasers have very interesting features making them perfect candidates of quantum batteries. Among them, we have found that the steady state of such systems can be easily made to be a *pure state*. This is a very good property, since it ensures that all the energy stored in the battery can be actually turned into physical work whenever necessary. Moreover, we have found that the charging temporal stability of these systems is extremely high, thus making these systems very reliable and very appealing as energy storage devices.

Main results:

- Ju-Yeon Gyhm, Dominik Šafránek and Dario Rosa, *Quantum charging advantage cannot be extensive without global operations*, under consideration in *Phys. Rev. Lett.*
- Vahid Shaghaghi, Varinder Singh, Giuliano Benenti and Dario Rosa, *Micromasers as quantum batteries*, in preparation.

Perspectives

The team is rather young, since it started in January 2021. During the first year of activity we have started the research lines stated above and we started to produce the first results, for a total of 5 papers (including publications and preprints) which appeared during the first year. In the near future, we plan to continue the projects already outlined. We are also starting to enter in the field of quantum computing and its connections with quantum many-body systems. Hence, we plan to extend our activities on this direction too.

Cooperations

Within the PCS, we collaborate closely with the group "Complex Condensed Matter Systems" and the group "Topological and Correlated Quantum Matter". Inside Korea, we have active connections on the study of K-complexity (University of Seoul, Seoul) and on the interplay between condensed matter problems and quantum gravity (APCTP, Pohang).

International cooperations include 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 magic (University of Massachusetts Boston, US) and quantum chaos and K-complexity (University of Cape Town, South Africa, IFAE, Spain and Hebrew University, Israel).

1.6.8 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 superconductors, 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:

- *Higher-Order Topological Insulator in Twisted Bilayer Graphene*
  Phys. Rev. Lett. 123, 216803 (2019)
- *Emergent Localization in Dodecagonal Bilayer Quasicrystals*
  Phys. Rev. B, 99, 245401 (2019)
- *Higher-Order Topological Instanton Tunneling Oscillation*
  Carbon 174 (2021)
- *Hinge Magnons from Non-collinear Magnetic Order in Honeycomb Antiferromagnet*
  Phys. Rev. B. 104, L060401 (2021)

Unconventional multi-band superconductivity. 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:

- *Pressure Induced Topological Superconductivity in the Spin-Orbit Mott Insulator GaTa4Se8*
  npj Quantum materials 5, 41 (2020)
- *Topological d+s wave superconductors in a multi-orbital quadratic band touching system*
  Phys. Rev. B, 100, 064509 (2019)
- *Topological d-wave Superconductivity and Nodal Line-Arc Intersections in Weyl Semimetals*

Phys. Rev. B, 100, 134512 (2019)

- *Multipolar superconductivity in Luttinger semimetals*
  Phys. Rev. Research 2, 023416 (2020)

- *Geometric Superconductivity in 3D Hofstadter Butterfly*
  arXiv:2007.16205 (2020, under review in Nature Communications).

- *Triplet-Superconductivity in Triple-Band Crossings*
  arXiv:1909.04015 (2019, under review in Communications Physics)

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:

- *Disorder-driven Phase Transitions of Second-order Non-Hermitian Skin Effects*
  Phys. Rev. B 104, L121101 (2021)

- *Strongly Coupled Photonic Moire Superlattices*
  arXiv:2108.14002 (2021, under review in Light: Science & Applications)

- *Length scale formation in the Landau levels of quasicrystals*
  arXiv:2106.07782 (2021, under review in Sciposts)

Future Perspectives

The division and the team were established in April 2021, with the arrival of Moon Jip Park. Currently, the team consists of four members, Dr. Moon Jip Park (Team leader), Dr. Kyoung Min Kim, Dr. Grigory Bednik and Dr. Sonu Verma. 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 collaborations 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).

1.6.9 Optics of Quantum Fluids and Nanomaterials

Team Leader: Sergei Koniakhin

Research Topics

Optics of Quantum Fluids and Nanostructures. This is a newly established Young Scientist Fellow (YSF) team at PCS. The starting date was 1 September 2021. The main focus of the team is on the optical properties of nanoparticles and other nanostructures and the various phenomena in quantum fluids based on exciton-polaritons in semiconductor microcavities. Concerning the optics of nanoparticles, Raman spectra of crystalline nanoparticles are actively investigated. Based on previous work of the team leader which developed precise Raman spectra calculation and the description of Raman peak broadening induced by lattice impurities, the focus is now on other mechanisms of optical phonon damping. The ultimate goal is to create a user friendly application for nanoparticle Raman spectra analysis with parameters including nano-powder parameters like the mean nanoparticle size and standard deviation, the shape of nanoparticles and the concentration and types of the impurities. One perspective is the application of artificial intelligence methods as an engine for this software.

Quantum fluids are studied with the main focus on quantum turbulence in artificial photonic lattices. The main goal will be to propose the experimental configuration for polaritonic platforms for the study of quantum turbulence and fractal structures of quantum vortices. In artificial photonic lattices, the gauge fields and topological defects in real and momentum space and their mapping will be investigated. We also aim to propose an experimental configuration for polaritonic platforms for experimental direct measurement and visualization of Green's functions. As a result, the theory developed for optical phonons and Raman spectra can be combined with polaritonic platforms, which will be a excellent example of convergence and synergy in theoretical physics.

The division and the team were established in September 2021, with the arrival of Sergei Koniakhin to IBS. The team currently has two members - Dr. Ihor Vakulchyk and Olha Bahrova.

Chapter 2

Selection of Research Results

Contents

2.1 Thermalization of weakly non-integrable many-body systems

T. Mithun, C. Danieli, M. Malishava, S. Flach

We address the way a macroscopic nonintegrable system will slow down its thermalization dynamics upon approaching an integrable limit. The celebrated Kolmogorov-Arnold-Moser (KAM) theorem is of little use here since its validity borders are known to deteriorate with increasing number of degrees of freedom (DoF). We therefore study thermalization dynamics beyond the KAM horizons and search for nontrivial classes of weakly nonintegrable macroscopic dynamics. Thermalization of nonintegrable many-body systems can be studied and addressed by testing either ergodicity or mixing or both.

Ergodicity ensures that a solution visits almost all states of the available phase space. Infinite time averages of observables will be equal to their phase space averages. For practical reasons only finite time averages (FTA) can be probed. We use the sensitivity of FTAs to initial conditions and compute distributions of FTAs through proper initial condition sampling. This allows us to quantify the dependence of FTA distributions on the averaging time T and their convergence to a δ-function in accordance with the ergodicity property [1–3]. The ambiguity in the choice of the observables is removed by focusing on the uniquely defined actions at the very integrable limit to be approached. We assume the action set to be countable, which in practice leads to model classes defined on spatial lattices. The integrable limits are then realized by either zeroing the strength of a nonlinear parameter analogous to the two-body interaction strength, or by zeroing the lattice coupling (hopping) strength. *Mixing* on the other side is probed by quantifying exponential growth of distances between neighboring trajectories. Usually the largest Lyapunov exponent is computed whose inverse sets the Lyapunov time T_Λ. FTA distributions will be T-independent for $T < T_\Lambda$ [1–3]. The entire Lyapunov spectrum was evaluated for macroscopic weakly nonintegrable nonlinear unitary maps [4].

The Hamiltonian $H(J,\theta) = H_0(J) + \epsilon H_1(J,\theta)$ where (J,θ) is a set of action and angle coordinates and H_0 is the integrable part. The non-integrable perturbation H_1 spans an interaction network between the actions of the integrable part and we consider the gradual limit $\epsilon \to 0$. In a local basis which is dictated by physics applications we considered lattice models to be invariant under discrete translations. We then find two different network types. For weak nonlinear perturbations H_1 imposes a *Long Range Network* (LRN), since the actions are related to normal modes extended in real space, and nonlinearity couples them all. On the other side, the gradual removal of the coupling strength on the lattice imposes a *Short Range Network* (SRN) due to the action of H_1 [1–4].

Consider an array of coupled Josephson junctions (JJ) as a paradigmatic model to test ergodicity time scales [1, 3]:

$$H(q,p) = \sum_{n=1}^{N} \left[\frac{p_n^2}{2} + E_J(1 - \cos(q_{n+1} - q_n)) \right].$$

It describes the dynamics of a chain of N coupled rotors with rotor momenta p_n and angles q_n. E_J controls the strength of the Josephson coupling. With periodic boundary conditions the system has two conserved quantities: the total energy H and the total momentum $L = \sum_{n=1}^{N} p_n$. Without loss of generality we set $L = 0$. The many-body dynamics is controlled by one parameter ϵ - the ratio of the energy density $h = H/N$ over the Josephson energy E_J: $\epsilon = h/E_J$. For $\epsilon \to 0$ the model approaches the integrable limit of a harmonic chain (simply replace $(1 - \cos x)$ by $x^2/2$ in the Hamiltonian). The actions are given by the extended normal mode solutions of this integrable model. The leading order nonintegrable perturbation follows form the quartic Taylor expansion term of the above cosine term similar to a quartic Fermi-Pasta-Ulam chain. The non-integrable perturbation spans a LRN among the normal mode actions. The width of the corresponding distribution of FTAs of a normal mode action is frozen up to the time scale $T_E > T_\Lambda$ and relaxes for larger averaging times $T > T_E$ as $1/T$ (see e.g. [2]). Up to a possible dependence on the chosen normal mode wave number, these LRNs show a homogeneous thermalization dynamics among all participating actions due to the long ranginess of the network. The ratio T_E/T_Λ is only weakly varying upon approaching the integrable limit.

The same JJ model allows for another integrable limit when $\tilde{\epsilon} = 1/\epsilon \to 0$ which is simply obtained by fixing E_J and gradually increasing h. The integrable Hamiltonian is given by a set of noninteracting rotors with corresponding actions p_n. The nonintegrable perturbation is the entire Josephson term in the JJ Hamiltonian. The perturbation spans a SRN among the actions. Again the distribution of FTAs of the actions is frozen up to the Lyapunov time T_Λ. However, at variance to the LRN, the freezing continues up to the ergodization time T_E which grows dramatically: T_E/T_Λ reaches 10^7 at modest values of $\tilde{\epsilon} = 0.1$ in Fig.1. Moreover, the width of the FTA distribution decays as $1/\sqrt{T}$ for $T > T_E$ as opposed to the $1/T$ decay in LRNs [3]. This dramatical slowing down of thermalization is due to the fact that not only the strength of chaotic resonances related to the largest Lyapunov exponent diminishes, but also their density in (real) action space does. As a result, more and more actions stay almost unchanged up to times $T_E \gg T_\Lambda$. Ergodization is reached by a slow diffusion process of the chaotic resonances, which explains the observed slow $1/\sqrt{T}$ decay of the FTA distribution width. As a consequence weak noise can be used to destroy chaotic resonances, slow down their diffusion and therefore ergodization and thermalization - a rather counter intuitive result observed in Ref. [3].

A recent study of the scaling of the entire Lyapunov spectrum of unitary map model in the proximity of an integrable limit showed that in units of the largest Lyapunov exponent the rescaled spectrum stays analytic upon approaching the integrable limit through a LRN [4]. This confirms that a LRN path towards an integrable limit is governed by just one diverging time scale T_Λ. The same study showed that the approaching of an integrable limit through a SRN results in a second diverging length scale and a non-analytic rescaled Lyapunov spectrum. The diverging length scale is directly related to the diminishing density of chaotic resonances, probably simply being their diverging inverse [4].

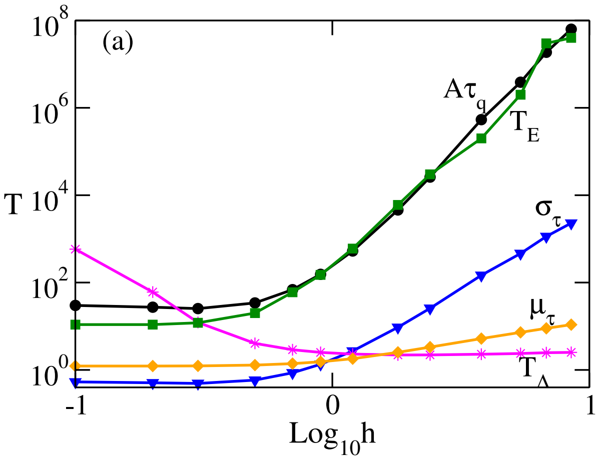

Figure 1: Time scales T_E (green squares) and T_Λ (magenta stars) vs the energy density $h = H/N$ for $E_J = 1$. Other data correspond to details of the FTA distributions: $A\tau_q$ (black circles), μ_τ (orange diamonds) and σ_τ (blue triangles) with $A = 130$, see Ref. [1] for details.

In summary, we identified two qualitatively different classes of weakly nonintegrable macroscopic systems characterized by a LRN or a SRN of the weak nonintegrable perturbation. LRN models show homogeneous thermalization, while SRN models are characterized by a dramatic slowing down and highly heterogeneous and fragile thermalization, with potential dramatic consequences upon quantization.

[1] T. Mithun, C. Danieli, Y. Kati, and S. Flach, Phys. Rev. Lett. **122**, 054102 (2019).

[2] C. Danieli, T. Mithun, Y. Kati, D. K. Campbell, and S. Flach, Phys. Rev. E **100**, 032217 (2019).

[3] T. Mithun, C. Danieli, M. V. Fistul, B. L. Altshuler, and S. Flach, Phys. Rev. E **104**, 014218 (2021).

[4] M. Malishava and S. Flach, Phys. Rev. Lett. 128, 134102 (2022); arXiv:2109.01361 (2021).

2.2 Floquet Anderson Localization of Two Interacting Discrete Time Quantum Walks

Merab Malishava, Ihor Vakulchyk, Mikhail Fistul, Sergej Flach

We study the localization properties of two interacting discrete time quantum walks in one dimension in the presence of disorder [1]. Each discrete time quantum walk (DTQW) is described by a Floquet unitary map defined on a chain of two-level systems described by a corresponding wave function. In the noninteracting case proper disorder induces Anderson localization with a gapless spectrum and unique localization length for all eigenstates [2]. We introduce a local contact interaction parametrized by a phase shift γ in each walker's wave function. As a result we witness a subdiffusive spreading of the wave-packet beyond the limits set by the single particle localization length ξ_1 and saturation at a new length scale $\xi_2 \gg \xi_1$.

We consider the dynamics of two quantum particles with an internal spin-like degree of freedom on a one-dimensional lattice. Each walker is characterized by a two-component wave function defined on a discrete chain of N sites. The wave function is embedded in a $2N$-dimensional Hilbert space.

The extension to the two interacting walks (TIW) is done straightforwardly by taking the tensor product of two single particle Hilbert spaces to arrive at a two particle wave function:

$$\Psi(t) = \sum_{n,m=1}^{N} \sum_{\alpha,\beta=\pm} \psi_{nm}^{\alpha\beta}(t)\alpha,\beta \otimes n,m.$$

The wave function $\Psi(t)$ is embedded in a $4N^2$-dimensional Hilbert space where $\alpha,\beta = \pm,\pm$ are basis vectors of two local two-level systems, and n,m are basis vectors in a two-dimensional square lattice.

The TIW evolution is obtained through a product of a TIW coin $\hat{W}$, shift $\hat{T}$ and interaction $\hat{G}$ operators acting on the wave function (see Fig.1):

$$\Psi(t+1) = \hat{T}\hat{W}\hat{G}\Psi(t).$$

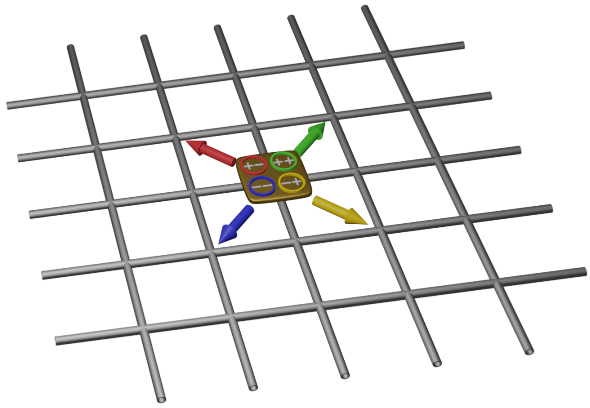

Figure 1: A schematic view of the TIW. The four components of the wave function on each site of a square lattice are shifted in different directions indicated by the arrows.

Here $\hat{G}$ is an interaction operator while the two-particle coin $\hat{W} = \hat{C} \otimes \hat{C}$ and shift $\hat{T} = \hat{S} \otimes \hat{S}$ operators are tensor products of the corresponding single-particle operators. The coin operator $\hat{C}$ is a unitary matrix given by

$$\hat{C} = \sum_{n=1}^{N} e^{i\varphi_n} \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \otimes nn.$$

The local unitary operators are 2x2 matrices. They are parametrized by one spatially independent angle θ which controls the hopping strength, and uncorrelated random angles $\varphi_n \in [-\pi,\ \pi]$ which play the role of a disorder potential.

The shift operator $\hat{S}$ of a single walk couples neighboring sites by shifting all the ψ_n^+ components one step to the right, and all the ψ_n^- components to the left:

$$\hat{S} = \sum_n nn+1 \otimes -- + \\ nn-1 \otimes ++.$$

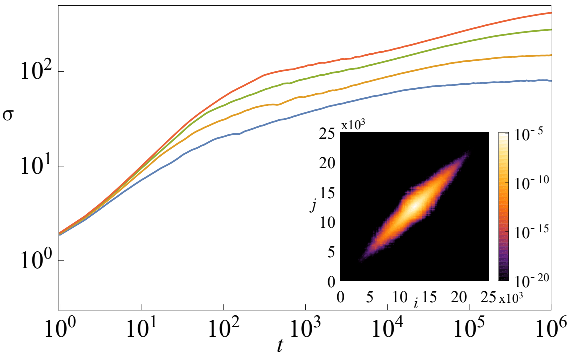

Figure 2: Time evolution of σ of a TIW for different values of $\theta = \pi/8, \pi/12, \pi/16, \pi/20$ from bottom to top. Here $\gamma = \pi$ and $N = 25000$. Inset: snapshot of the probability distribution p_{ij} for $\theta = \pi/20$ at $t = 10^6$, showing strongly anisotropic wave packet spreading.

The local Hubbard-like contact interaction between the two DTQWs is given as:

$$\hat{G} = \mathbb{1}_c \otimes \mathbb{1}_p + \left(e^{i\gamma} - 1\right) \mathbb{1}_c \otimes \hat{N},$$

where γ is the interaction strength parameter. $\hat{N} = \sum_i n, nn, n$ is a projector on the diagonal of the coordinate space, $\mathbb{1}_c$ is the 4×4 unity matrix in the coin space, and $\mathbb{1}_p$ is the $N^2 \times N^2$ unity matrix in the position space.

A unique feature of DTQWs is the ability to control the localization length by means of the angle parameter θ. In the single particle case all eigenstates have the same localization length [2]:

$$\xi_1(\theta) = -\frac{1}{\ln(|\cos\theta|)}.$$

Our goal is to compute a length scale proportional to the enhanced localization length ξ_2 and compare to $\xi_1(\theta)$ for different values of θ.

We follow the wave function probability distribution in the coordinate space of both DTQWs

$$p_{nm}(t) = \sum_{\alpha,\beta=\pm} \left|\psi_{nm}^{\alpha\beta}\right|^2.$$

To assess the TIW localization length scales we will project p_{nm} onto a one-dimensional coordinate space and compute the density distribution $v_n = \sum_m p_{nm}(t)$ similar to a charge density distribution of two indistinguishable electrons. We finally evaluate the standard deviation

$$\sigma\left[\{v_n\}\right] = \left(\sum_n n^2 v_n - \left(\sum_n n v_n\right)^2\right)^{1/2}.$$

We evolve a system of size $N = 25000$ up to time $t_{\max} = 10^6$. We follow the time dependence of the standard deviation σ for various values of the angle θ. These results are presented in Fig. 2 (solid lines). $\sigma(t)$ shows ballistic-like growth ($\sigma \propto t$) up to $\sigma \sim \xi_1$ in analogy to the noninteracting case. During this first part of the dynamics, the wave packet spreads up to a length scale of the order of the single particle localization length ξ_1. At variance to the noninteracting case, the interacting dynamics continues beyond the limits set by the single particle DTQW Anderson localization. The corresponding growth of σ with time is close to a sub-diffusive one $\sigma \propto t^\alpha$ with $\alpha \leq 0.5$. We also estimate the saturation values $\sigma(t \to \infty)$ and conclude that the localization length $\xi_2 \sim \xi_1^{1.2}$ [1].

To conclude, we analyzed the interplay of disorder and interaction in the Floquet Anderson localization problem of two interacting discrete time quantum walks. We choose maximal disorder strength and control the localization length using the mixing parameter of unitary map evolution. We add a local contact interaction, which is parametrized by a phase shift γ. A wave packet is spreading subdiffusively beyond the bounds set by ξ_1 and saturates at a new length scale $\xi_2 \gg \xi_1$. For the assumed strongest interaction case $\gamma = \pi$ we identify a new length scale $\xi_2 \gg \xi_1$, which follows approximately $\xi_2 \sim \xi_1^{1.2}$.

[1] Merab Malishava, Ihor Vakulchyk, Mikhail Fistul and Sergej Flach, Phys. Rev.B **101**, 144201 (2020).

[2] I. Vakulchyk, M. V. Fistul, P. Qin, and S. Flach, Phys. Rev. B **96**, 144204 (2017).

2.3 Many-Body Flatband Localization

Carlo Danieli, Alexei Andreanov, Sergej Flach

We generate translationally invariant systems exhibiting many-body localization from all-bands-flat single-particle lattice Hamiltonians dressed with suitable short-range many-body interactions [1]. This phenomenon, dubbed *many-body flatband localization* (MBFBL), is based on symmetries of both single-particle and interaction terms in the Hamiltonian, and it holds for any interaction strength and any spatial dimension.

We consider a translationally invariant many-body Hamiltonian $\hat{\mathcal{H}}$ on a lattice

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_{\text{sp}} + \hat{\mathcal{H}}_{\text{int}} \ , \hat{\mathcal{H}}_{\text{sp}} = \sum_k \hat{f}_k \ , \hat{\mathcal{H}}_{\text{int}} = \sum_\kappa \hat{g}_\kappa$$

where both single particle part and interaction are expressed as sums of local operators $\hat{f}_k$ and $\hat{g}_\kappa$. The integers k and κ label unit cells of the lattice in a direct space for two *distinct* unit cell choices A and B. Both unit cells contain ν lattices sites or single particle levels. The local operators are expressed through creation and annihilation operators $\hat{c}^\dagger_{k,a}, \hat{c}_{k,a}$ which create or annihilate a single particle on a given lattice site k, a with $1 \le a \le \nu$:

$$\hat{f}_k = \sum_{a,b=1}^{\nu} t_{ab} \hat{c}^\dagger_{k,a} \hat{c}_{k,b} + \text{h.c.}$$

$$\hat{g}_\kappa = \sum_{\alpha,\beta,\gamma,\delta=1}^{\nu} J_{\alpha\beta\gamma\delta} \hat{c}^\dagger_{\kappa,\alpha} \hat{c}^\dagger_{\kappa,\beta} \hat{c}_{\kappa,\gamma} \hat{c}_{\kappa,\delta} + \text{h.c.},$$

for the two-body *interaction* Hamiltonian $\mathcal{H}_{\text{int}}$.

Both single particle and interaction Hamiltonians are *semi-detangled* (SD) if $[\hat{f}_k, \hat{f}_{k'}] = [\hat{g}_\kappa, \hat{g}_{\kappa'}] = 0$ for any k, k', κ, κ'. The spectrum of the single particle eigenvalue problem with $\mathcal{H}_{\text{sp}}$ yields ν flatbands with each being an eigenenergy of any of the local operators $\hat{f}_k$, implying full localization and absence of any transport. The same is true for $\hat{\mathcal{H}}_{\text{int}}$. *Fully-detangled* (FD) $\hat{\mathcal{H}}_{\text{sp}}, \hat{\mathcal{H}}_{\text{int}}$ are functions of the particle number operators $\hat{n} = \hat{c}^\dagger \hat{c}$ only, e.g. $t_{ab} = t_{aa}\delta_{a,b}$ or $J_{\alpha\beta\gamma\delta} = J_{\alpha\beta\alpha\beta}\delta_{\alpha,\gamma}\delta_{\beta,\delta}$, and do not move any particles from any lattice site to any other one. We refer to all the other types of Hamiltonians as *non-detangled* (ND).

We generate MBFBL Hamiltonians by choosing any of the three combinations:

[width=3.75em]$\hat{\mathcal{H}}_{\text{sp}}\hat{\mathcal{H}}_{\text{int}}$	SD	FD
SD	—	MBFBL
FD	MBFBL	MBFBL

Indeed, the resulting interacting Hamiltonian $\hat{\mathcal{H}}$ preserves full localization of particles if $\hat{\mathcal{H}}_{\text{sp}}$ or $\hat{\mathcal{H}}_{\text{int}}$ are SD; and in addition heat if both $\hat{\mathcal{H}}_{\text{sp}}, \hat{\mathcal{H}}_{\text{int}}$ are FD. We then perform a unitary transformation (rotation) on each unit cell in either of the two unit cell choices A, B. This results in general in some complicated Hamiltonian with $\hat{\mathcal{H}}_{\text{sp}}$ being non-detangled and $\hat{\mathcal{H}}_{\text{int}}$ being fully or semi-detangled, or vice versa depending on which unit cell type the transformation was applied to. Furthermore these transformations can be chosen unit cell dependent resulting in non-translationally invariant Hamiltonians. This algorithm works for any number of bands ν of $\mathcal{H}_{\text{sp}}$, in any dimension, and for any type of many-body statistics. Additionally it also gives an extensive set of analytically known local integrals of motion [1].

Experimental feasibility favors fully-detangled $\hat{\mathcal{H}}_{\text{int}}$, such as density-density interactions. Next we conveniently restate $\hat{\mathcal{H}}_{\text{sp}}$ in the unit cell representation B of $\hat{\mathcal{H}}_{\text{int}}$ and apply the subsequent unitary transformations that recast $\hat{\mathcal{H}}_{\text{sp}}$ to a non-detangled Hamiltonian and keep $\hat{\mathcal{H}}_{\text{int}}$ fully-detangled. This change of unit cell introduces hopping terms between neighboring unit cells in each local Hamiltonian $\hat{f}_\kappa$. A possible $d = 1$ $\hat{\mathcal{H}}_{\text{sp}}$ with nearest-neighboring unit cells hopping reads

$$\hat{\mathcal{H}}_{\text{sp}} = \sum_\kappa \hat{f}_\kappa = \sum_\kappa \left[\frac{1}{2} \hat{C}^{\dagger T}_\kappa H_0 \hat{C}_\kappa + \hat{C}^{\dagger T}_\kappa H_1 \hat{C}_{\kappa+1} \right]$$

where we grouped the annihilation (creation) operators $\hat{c}_{\kappa,a}$ ($\hat{c}^\dagger_{\kappa,a}$) in ν-dimensional vectors $\hat{C}_\kappa(\hat{C}^\dagger_\kappa)$. The matrices H_0, H_1 describe intraand inter-cell hopping respectively, and are chosen so as to enforce the SD condition $[\hat{f}_\kappa, \hat{f}_{\kappa'}] = 0$ for all κ, κ'. This is only one of the infinitely many realizations of a SD single particle Hamiltonian.

The fully-detangled two-body interaction Hamiltonian $\hat{\mathcal{H}}_{\text{int}}$ is defined by $J_{\alpha\beta\gamma\delta} = J_{\alpha\beta\alpha\beta}\delta_{\alpha,\gamma}\delta_{\beta,\delta}$ for each local component $\hat{g}_\kappa$: $J_{\alpha\beta\alpha\beta} = 1$ for $\alpha = \beta$ and $J_{\alpha\beta\alpha\beta} = 2$ for $\alpha \neq \beta$. For two bands $\nu = 2$ this gives an *extended Hubbard* interaction among the sites $\hat{a}_\kappa = \hat{c}_{\kappa,a}, \hat{b}_\kappa = \hat{c}_{\kappa,b}$:

$$\begin{aligned}\hat{\mathcal{H}}_{\text{int}} &= \sum_\kappa \left[\hat{a}_\kappa^\dagger \hat{a}_\kappa^\dagger \hat{a}_\kappa \hat{a}_\kappa + \hat{b}_\kappa^\dagger \hat{b}_\kappa^\dagger \hat{b}_\kappa \hat{b}_\kappa + 2\hat{a}_\kappa^\dagger \hat{a}_\kappa \hat{b}_\kappa^\dagger \hat{b}_\kappa\right] \\ &= \sum_\kappa \left[\hat{n}_{a,\kappa} + \hat{n}_{b,\kappa} - 1\right]\left[\hat{n}_{a,\kappa} + \hat{n}_{b,\kappa}\right]\end{aligned}$$

with $\hat{n}_{a,\kappa} = \hat{a}_\kappa^\dagger \hat{a}_\kappa$ and $\hat{n}_{b,\kappa} = \hat{b}_\kappa^\dagger \hat{b}_\kappa$. Then $\hat{\mathcal{H}}_{\text{int}}$ is preserved as fully-detangled with the same coefficients $J_{\alpha\beta\gamma\delta}$ by any 2×2 unitary transformation

$$U_{ab}: \begin{cases}\hat{c}_{\kappa,a} = z\hat{d}_{\kappa,a} + w\hat{d}_{\kappa,b} \\ \hat{c}_{\kappa,b} = -w^*\hat{d}_{\kappa,a} + z^*\hat{d}_{\kappa,b}\end{cases}$$

parameterized by two complex numbers z, w such that $|z|^2 + |w|^2 = 1$ and any pair of sites $\hat{c}_{\kappa,a}, \hat{c}_{\kappa,b}$.

The simplest MBFBL network with $\nu = 2$ bands is based on the extended Hubbard interaction and the SD Hamiltonian $\hat{\mathcal{H}}_{\text{sp}}$ with

$$H_0 = \begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}, \qquad H_1 = \begin{pmatrix}0 & t\\ 0 & 0\end{pmatrix},$$

and a free complex parameter t. The structure of $\hat{\mathcal{H}}_{\text{sp}}$ and $\hat{\mathcal{H}}_{\text{int}}$ is shown in Fig. 1(a) with solid lines and red shaded rods respectively. The rotation U_{ab} recasts H_0, H_1 as

$$H_0 = \begin{pmatrix}|z|^2 & z^*w\\ zw^* & |w|^2\end{pmatrix}, \; H_1 = t\begin{pmatrix}-z^*w^* & (z^*)^2\\ -(w^*)^2 & z^*w^*\end{pmatrix},$$

and makes Hamiltonian $\hat{\mathcal{H}}_{\text{sp}}$ non-detangled while $\hat{\mathcal{H}}_{\text{int}}$ remains fully-detangled. The resulting MBFBL network is shown in Fig. 1(b).

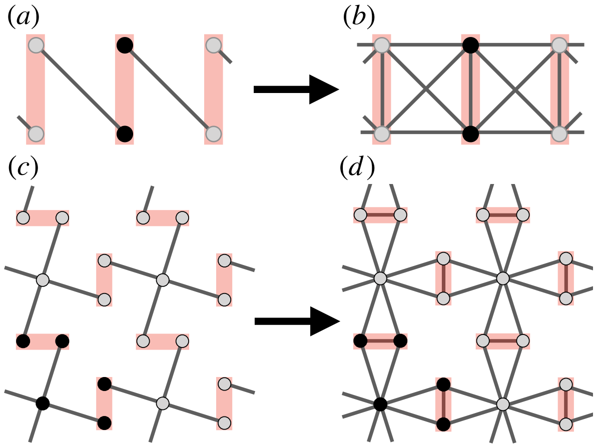

Figure 1: (a,b) One-dimensional two-band MBFBL network with $\hat{\mathcal{H}}_{\text{sp}}$ SD (a) and ND (b). The black circles indicate the unit cell choice, the solid lines correspond to sites connected by $\hat{\mathcal{H}}_{\text{sp}}$ before (a) and after (b) the rotation, and the red-shaded rods indicate the extended Hubbard terms of $\hat{\mathcal{H}}_{\text{int}}$. (c,d) Same as (a,b) for a two-dimensional MBFBL network.

Many-body flatband localization implies strict many-body localization of particles irrespective of interaction strength and dimensionality – with an example of a two-dimensional MBFBL network with $\nu = 5$ bands shown in Fig. 1(c,d). A novel and unique feature of these systems is the existence of unitary mappings that recast them into a detangled form. This very property can be employed to study the impact of additional perturbations of the proposed networks which lift MBFBL and modify the analytically known local integrals of motion [1] in a systematic and analytical form. Hence, these systems offer innovative, experimentally feasible and powerful tools to potentially perform systematic analytical studies of conventional properties of MBL networks which typically rely on heavy numerical studies.

[1] Carlo Danieli, Alexei Andreanov, and Sergej Flach, Phys. Rev. B 102, 041116(R) (2020).

2.4 Metal-insulator transition in infinitesimally weakly disordered flatbands

Tilen Čadež, Yeongjun Kim, Alexei Andreanov, Sergej Flach

We demonstrate that flatbands are sensitive and react differently to very weak perturbations that appear to be similar. A tiny change in the weak perturbation causes the entire system to go from a metal to an insulator. As a minimal model we consider a family (or a manifold) of all-bands-flat (ABF) lattices, which are perturbed by an infinitesimal onsite disorder [1].

The starting point of ABF construction is a diagonal Hamiltonian consisting of two macroscopically degenerate flat bands at energies $E_a = -E_b = \Delta/2$, separated by the energy gap Δ, which we refer to as fully-detangled (FD) parent Hamiltonian $\mathcal{H}_{\mathrm{FD}}$. The manifold of ABF Hamiltonians $\mathcal{H}_0$ is then constructed systematically in one, two, and three dimensions by applying a unitary transformation U on the parent Hamiltonian

$$\mathcal{H}_0 = U\mathcal{H}_{\mathrm{FD}}U^\dagger.$$

We choose the unitary transformation as a combination of a finite number of local unitary transformations (LUT), $U = \prod_{i=1}^{d+1} U_i$, with d being the dimensionality of the system and where each LUT is parametrized by a set of manifold angles. For simplicity we set all manifold angles to be equal and denote them by θ. The construction in $d = 1$ is schematically shown in panels (a)-(c) of Fig. 1.

A natural question is how different members of this manifold react to perturbations? We consider the case of on-site disorder $\mathcal{H}_{\mathrm{dis}} = W\mathcal{D}$ added to the ABF Hamiltonian $\mathcal{H}_0$, where $\mathcal{D}$ is a diagonal matrix, with the diagonal elements being random real numbers with box distribution within $[-1/2, 1/2]$. The disorder strength W is assumed infinitesimal: $W \ll \Delta$. In this limit the flatbands are only slightly broadened and one can neglect the coupling between the eigenstates of different flatbands. Therefore the perturbed Hamiltonian $\mathcal{H}_0 + \mathcal{H}_{\mathrm{dis}}$ is well approximated by the first-order energy correction from degenerate perturbation theory:

$$WP_{a,b}U^\dagger\mathcal{D}UP_{a,b}|\psi\rangle = \delta E_{a,b}|\psi\rangle,$$

where $\delta E_{a,b}$ is a correction to the flatbands energy $E_{a,b} = \pm\Delta/2$ and $P_{a,b}$ is the projector onto the respective flat band $E_{a,b}$. The disorder strength W appears only as an overall scaling factor and does not affect the eigenstates in the above equation. Therefore, it can be factored out, giving a new effective Hamiltonian that is W-independent, implying that eigenstate properties are disorder strength independent for weak disorder. We refer to this resulting Hamiltonian as the *scale free model.* This means that the infinitesimal disorder always affects the eigenstates, which are yet independent of W in the limit $W \ll \Delta$. The scale free model is the foundation for the analysis of the localization properties of the weakly disordered models discussed below.

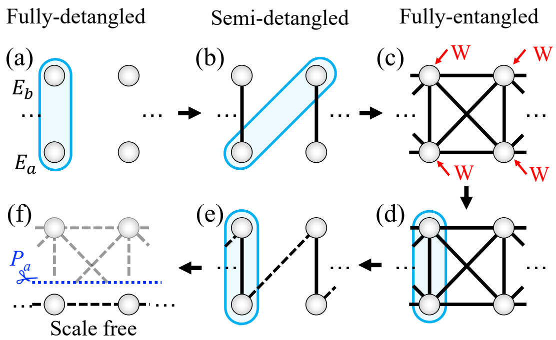

Figure 1: One dimensional two band ABF system: We start in FD basis (a). Entangling with LUTs is depicted in (b)-(c). After adding onsite potential disorder in (c) detangling back is depicted in (e)-(f). Finally in (f), the upper part is projected out and we obtain the scale free model.

We derived the scale free models for ABF lattices with infinitesimal on-site disorder for $d = 1, 2, 3$ following the above prescription. These scale free models in $d = 1, 2, 3$ have only the nearest and next-nearest neighbor hoppings, that are random, with zero average. The full procedure described above for the $d = 1$ case is depicted schematically in Fig. 1.

We evaluate the impact of infinitesimal disorder on the ABF model by numerically studying the localization properties of the scale free Hamiltonian. For that we analyze the participation numbers PN of the eigenstates and the spectral statistics of the eigenenergies, namely the ratio of adjacent gaps (ROAG) r. The PN of an eigenstate μ, is defined as $\mathrm{PN}_\mu = (\sum_{\mathbf{e}} \psi^4_{\mu,\mathbf{e}})^{-1}$, where $\psi_{\mu,\mathbf{e}}$ is the eigenstate amplitude in a chosen basis. The localization properties are extracted from the scaling of the average PN with the system size $\langle \mathrm{PN} \rangle \sim L^\alpha$, where $\alpha = 0$ and $\alpha = d$ correspond to localized and extended states, respectively. In the absence of disorder the PN is equal to 1 in the FD basis, which means that the eigenstates are compactly localized. In contrast, $\langle \mathrm{PN} \rangle$ of the scale free model in all d differs significantly from the case of the CLS.

In $d = 1, 2$, the PN increases with θ and the maximum is reached for $\theta = \pi/4$, which also maximizes the hopping matrix elements in the scale free model. However $\langle \mathrm{PN} \rangle$ does not scale with the system size, which means that all the eigenstates remain localized (not shown here).

In contrast we see a strikingly different behaviour in $d = 3$. The energy resolved average PN exponent α and the average ROAG r as a function of the ABF manifold angle θ for $d = 3$ are shown in panels (a) and (b) of Fig. 2, respectively. There are two clearly distinct regions observed: one with $\langle \mathrm{PN} \rangle$ not scaling with system size ($\alpha \to 0$) and $\langle r \rangle \sim 0.386$, which corresponds to localized eigenstates and Poisson distribution of eigenenergies; and another with $\langle \mathrm{PN} \rangle$ increasing with the system size with exponent ($\alpha \to d = 3$) and $\langle r \rangle \sim 0.531$, corresponding to extended eigenstates and the level statistics of the Gaussian orthogonal ensemble. Therefore we identify the former as an insulator and the latter as a metal. From panels (a) and (b) of Fig. 2, we also observe mobility edges - the states at the band center are extended while those at the band edge are localized. Panels (c) and (d) show the exponent α and the average ROAG as a function of the ABF manifold angle at the flatband energy for different system sizes, confirming the metal-insulator transition in weakly perturbed three dimensional ABF system driven by the variation of the ABF manifold parameter.

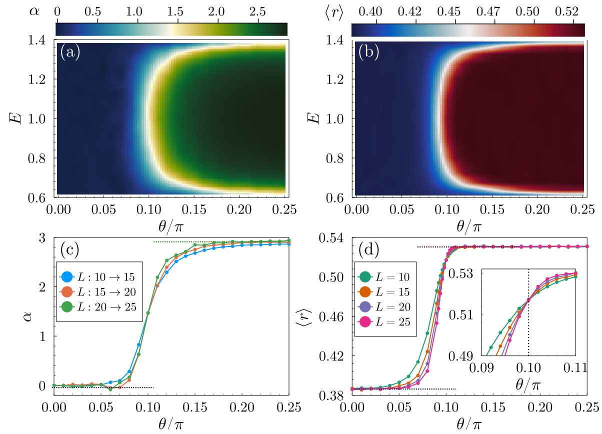

Figure 2: Panels (a) and (b) show the energy resolved exponent α ($\langle \mathrm{PN} \rangle \sim L^\alpha$) and the average ROAG $\langle r \rangle$ at weak disorder as a function of manifold angle θ. Two distinct phases are clearly identified, with a white region denoting the metal-insulator transition. Panels (c) and (d) show α and $\langle r \rangle$ as a function of the manifold angle θ at the flat band energy $E = 1$, respectively. The inset in panel (d) shows the zoom into the transition region at critical value $\theta_c/\pi = 0.1$. Number of unit cells used is L^3.

To conclude we have studied all-bands-flat systems in the presence of weak on-site disorder, and demonstrated that different ABF lattices react differently to the weak onsite disorder perturbation, no matter how weak the perturbation is. In $d = 3$ we found a metal-insulator transition driven by the change in the LUT manifold angles.

[1] Tilen Čadež, Yeongjun Kim, Alexei Andreanov, and Sergej Flach, Physical Review B, 104(18), L180201 (2021).

2.5 Manipulation of valley isospins in strained graphene for valleytronics

N. Myoung, H. Choi, H.C. Park

We demonstrate mesoscopic transport through quantum states in graphene quantum Hall system with a p–n junction and a local strain [1]. The strain plays the roles of the pseudo-magnetic field rotating phase and the defect manipulating quantum states.

For graphene nanoribbons, it has been shown that quantum Hall conductance across a p–n junction depends on the orientation angle between valley isospins at the edges in each region. In the presence of strain, the valley-isospin dependence of quantum Hall effects in armchair graphene nanoribbons can be well formulated by

$$G_D = \frac{G_0}{2}\left[1 - \cos\left(\Phi + \Phi_{ps}\right)\right], \qquad (1)$$

where $G_0 = 2e^2/h$, Φ is the angle between valley isospins, and Φ_{ps} is the net phase acquired from the gauge fields along the interface channel. G_D is the quantum Hall conductance across the p–n junction, measured via diagonal leads. It is worth mentioning that Φ_{ps} is continuously given, whereas Φ is given by three-fold values: π or $\pm\pi/3$ for metallic and semiconducting cases, respectively. In this Letter, we set $\Phi = \pi$. When a Gaussian-deformation is created near the p–n junction, the valley isospin rotates as a consequence of phase acquirement Φ_{ps}, such that G varies. The goal of this work is to propose a feasible way of manipulating valley isospins through the strain engineering of graphene.

The conductance resonances appear for relatively stronger strain cases, as demonstrated by the diagonal lines along the G_D map in Fig. 1(a). Owing to the anti-symmetry of the p–n junction, the G_D and Fano resonance lines exhibit isotropic spectra with respect to E_F. These resonances can be understood as consequences of quantum interference between the extended states in the interface channel and the localized states in the strained region,or so-called Fano resonance. The diagonal resonance lines imply that the energy levels of the localized states in the strained region are dependent on h_0: with increasing strain strength, Dirac fermions more strongly localize, so that the energy levels of the localized states shift from the lowest LLs in each region ($E_F \simeq \pm 0.1$ eV).

Meanwhile, as shown in Fig. 1(b), there are two distinct types of resonance lines denoted by orange/pink and green circles. Probability density maps for each case are given in Fig. 1(c)–(e), showing single- and double-site localizations. These localized states are regarded as if a single quantum dot or double quantum dots are formed in the strained region. Such emergence of strain-induced quantum dots can be understood by seeing how the effective potential is shaped. It is also noticeable that a crossing behavior is observed when two single-dot resonances intersect at $E_F = 0$ eV for $h_0 = 4.2$ nm, whereas an anti-crossing behavior is observed when the single- and double-dot resonances meet near $E_F = 0.025$ eV for $h_0 = 4.9$ nm. Such crossing/anti-crossing behaviors originate from the valley-polarization of the localized states in strained graphene. The single-dot localized states shown in Fig. 1(c) and (d) correspond to the K and K' valleys, respectively, while the double-dot localized state in Fig. 1(e) corresponds to the K' valley. With a lack of inter-valley scattering in this study, it is straightforward to see the crossing behavior between the single-dot resonances because of their opposite valley polarizations. For the same reason, it is clear that the anti-crossing behavior between the single- and double-dot resonances comes from their identical valley polarizations.

In summary, we have studied the influence of local strain on quantum Hall conductance across a p–n interface in graphene. We revealed that the valley-isospin dependence of the quantum Hall conductance is modulated by the presence of local strain near the interface channel. Results indicated that quantum Hall conductance across the p–n interface

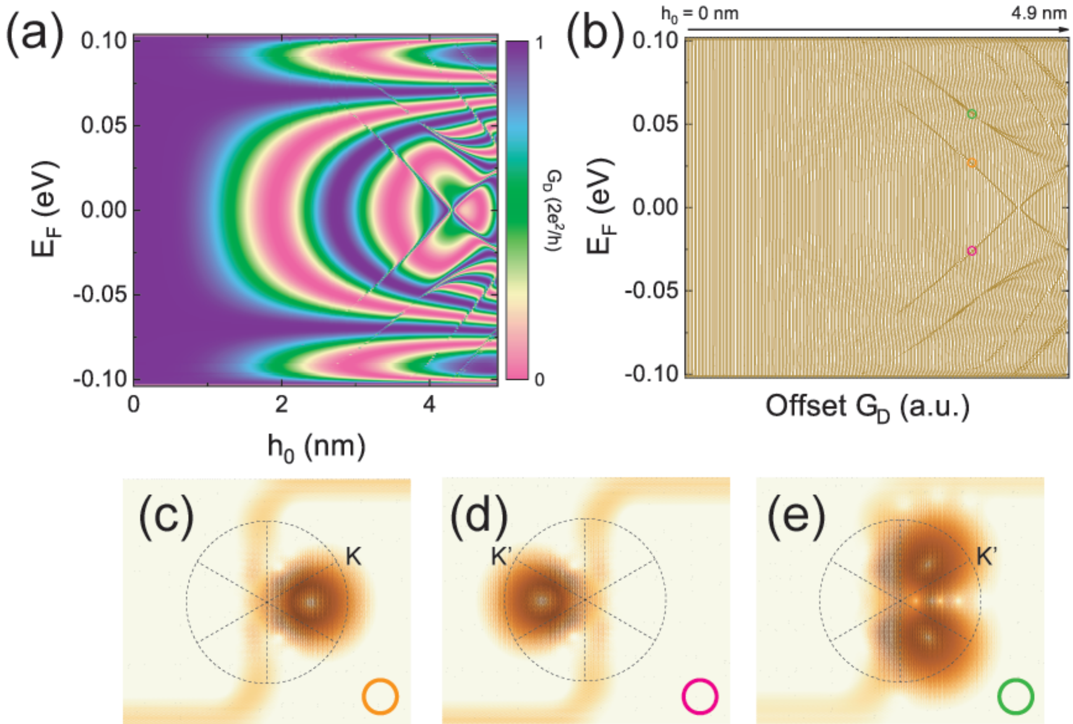

Figure 1: (a) Color map of G_D for $\sigma = 7.4$ nm as a function of E_F and h_0. (b) Conductance spectra versus E_F for various h_0 from 0 to 4.9 nm with 0.025-nm steps. (c)–(e) Probability current density maps for different Fano resonance lines denoted by orange, red, and green circles in (b). Dashed lines are eye-guides indicating the strained regions divided into six areas with alternating pseudo-magnetic field distributions.

no longer exhibits a clear plateau but rather an oscillating behavior with respect to strain strength. Such conductance oscillations originate from the rotations of the valley isospins because of the strain-induced pseudo-magnetic field. We have theoretically demonstrated that this valley-isospin rotation indeed occurs by the phase acquired by Dirac fermions while traveling through the strained region. Finally, we discussed the emergence of Fano resonances as evidence for the existence of localized states in a local strain. The strain-induced localized states are regarded as valley-resolved quantum dots in either single or double form.

Our findings in this work give rise to two significant implications in the field of graphene-based valleytronics. First, the conductance oscillation due to strain-induced valley-isospin rotation delivers a realizable approach to manipulate valley isospins in graphene quantum Hall devices, which means that the transport properties of such devices could be controllable via strain engineering. Second, the emergence of Fano resonances with the valley-resolved localized states possesses a great deal of potential for a novel type of valleytronic application based on graphene. Furthermore, the self-assembled localized states in the strained region may open an efficient means of fabricating a perfectly symmetric configuration of double or triple quantum dots.

[1] Nojoon Myoung, Hyungkook Choi, and Hee Chul Park, Carbon, **157**, 578 (2020).

2.6 Machine learning approach to the recognition of nanobubbles in graphene

T. Song, N. Myoung, H. Lee, H.C. Park

We propose a means to recognize the presence of nanobubbles in graphene by analyzing electronic properties based on a machine learning approach [1]. Our machine learning algorithm efficiently classifies the density of states spectra by the height and width of the nanobubbles, even in cases with a substantial magnitude of noise. The machine-learning-based analysis of electronic properties proposed in this study may introduce a changeover in the probing of nanobubbles from image-based detection to electrical-measurement-based recognition.

The electronic properties of nanobubbles are characterized by the density of states (DOS) $D(E)$ in experiments using tunneling spectroscopy with energy E. If we have a one-to-one correspondence between the geometric shapes and the DOS, we can assign a measurement to each nanobubble. However, a bottleneck is encountered when directly classifying the physical information of the nanobubbles as continuous variables, such as sizes that characterize the strength of strain. Here, machine learning (ML) supports the huge data analysis, easily providing the physical information of nanobubbles, shapes, and $D(E)$ through numerical calculation in a theoretical model. In this way, we expect to give a clue about the physical information of nanobubbles to experimentalists by applying widely used ML analysis.

We propose in this work an efficient route toward probing and examining the nanobubbles that emerge in quantum Hall graphene devices through an ML tool based on a two-dimensional (2D) convolutional neural network (CNN) algorithm, as shown in Fig. 1. The training datasets of $D(E)$ with different nanobubble configurations are computed by the KWANT package. In the presence of a nanobubble, characteristic peaks emerge in the DOS spectra, of which energies are dependent on the height and width of the nanobubble. Note that the individual DOS spectra from the different nanobbubles are distinguished from each other, so that our ML kernel is convinced of undergoing one-to-one mapping. We find that the trained ML kernel well predicts these nanobubble heights and widths. In the end, our approach allows us not only to detect the presence of nanobubbles in a graphene device but also to characterize the properties of the nanobubbles.

The trained ML kernel was tested on the newly generated $\tilde{D}(E)$ with various η. During the training, the MSE loss function is defined as $\mathrm{MSE} = \langle |\sigma^{\mathrm{true}} - \sigma^{\mathrm{pred}}|^2 + |h_0^{\mathrm{true}} - h_0^{\mathrm{pred}}|^2 \rangle$, where the bracket $\langle \cdot \rangle$ denotes the ensemble average for all applied cases, and the superscripts denote the parameters of the ground truth of $\tilde{D}(E)$, "true", and the output of our machine kernel, "pred". Typical MSE values reach $\mathcal{O}(10^{-2})$ before showing overfitting. In our study, overfitting can be easily detected by an incremental increase in validation error.

In order to test for the recognition of electronic structures originating from nanobubbles, we define the maximum strength of the strain-induced pseudomagnetic field as follows,

$$\tilde{B}(\sigma, h_0) = \frac{h_0^2}{\sigma^3}. \tag{1}$$

This parameter, $\tilde{B}$, is just one possible representative physical quantity to test the trained machine's ability to recognize electronic structures, following from its training to infer geometric factors of nanobubbles.

In summary, we have proposed a means to recognize nanobubbles via ML in graphene using DOS spectra. In the detection of nanobubbles, which are generally unavoidable and play a crucial role in electronic transport in graphene, image-based methods may be limited in directly probing their electronic structures. It would therefore be beneficial to confirm the presence of nanobubbles in devices and characterize them via their electronic structures. Thus, our approach may provide an advantage

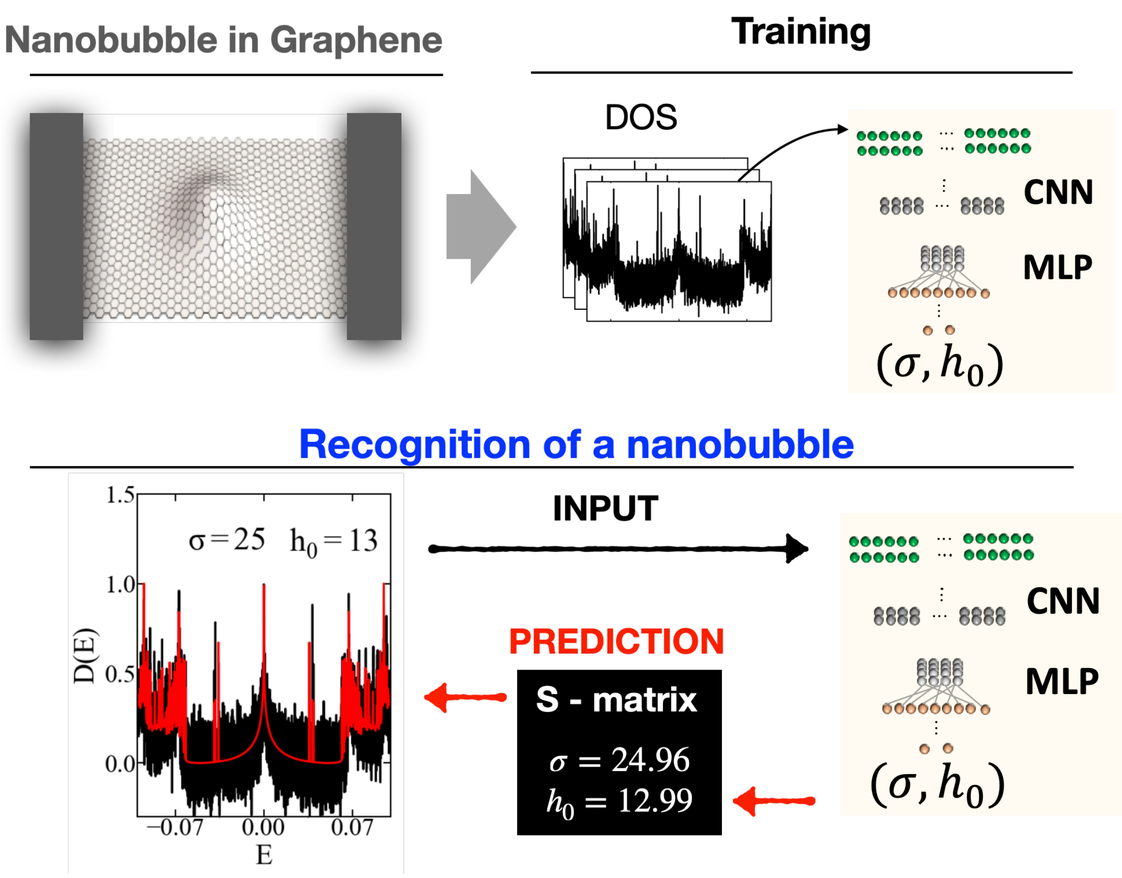

Figure 1: Schematic figures of our approach to nanobubble detection by ML. We suppose that a DOS obtained via experiment is characterized by a nanobubble in a graphene nanoribbon. For ML training, the DOS spectra, $D(E)$, is calculated by KWANT with two model parameters: height (h_0) and width (σ). After preprocessing, a 2D array of $[E, \tilde{D}(E)]$ as the input and the label (σ, h_0) as the desired output are used to optimize our ML kernel. We consider convolutional neural network (CNN) layers to extract the input features, and multilayer perceptron (MLP) layers are applied as the readout module to extract the labels.

in dealing with individual graphene nanobubbles in electronic devices like qubits by recognizing its electronic structure.

Here, we prepared the DOS spectra from S-matrix theory based on a Gaussian nanobubble model. To apply DOS spectra as inputs of the ML kernel, we designed preprocessing steps, one of which adds white noise to secure a suitable supply of training data and also possibly mimic unavoidable measurement noise. We tested various types of neural nets, activation functions, and cost functions. The trained ML kernel successfully predicts (σ, h_0) pairs in considerable noise strength. The trained ML kernel showed the best performance near the specific strength used in the training dataset, and successfully covered the areas below this noise strength. The trained ML kernal is shown to be a good method for recognizing nanobubbles formed in graphene samples with a sufficient accuracy, by means of analyzing DOS spectra.

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2.7 Valley Acoustoelectric Effect

A. V. Kalameitsev, V. M. Kovalev, I. G. Savenko

Two-dimensional materials (2D materials), such as transition metal dichalcogenides [1], possess symmetry properties similar to graphene. Their primary feature is that the valleys K and K′ in the Brillouin zone connect by the time reversal symmetry. Consequently, the chiralities of the K and K′ bands turn out opposite, and in addition to conventional momentum and spin of the two-dimensional electron gas (2DEG), 2D materials acquire an additional *valley index* degree of freedom. Moreover, their spectra manifest large gaps in the optical range, epitomizing various valley-resolved phenomena [2].

Only few phenomena distinguish Bloch electrons from free charges, and one of them is the Berry effect [3], which, in particular, influences the carriers of charge subject to a mechanical force $e\mathbf{E}$, where $\mathbf{E}$ is an external electric field and e is the elementary charge. It happens since the group velocity of a Bloch electron acquires an additional anomalous term $e\mathbf{E}\times\mathbf{\Omega}_\mathbf{k}$, where $\mathbf{k}$ is the momentum of the particle and $\mathbf{\Omega}_\mathbf{k}$ is the Berry curvature. In the framework of the linear response theory, the matrix of the velocity operator acquires nonzero off-diagonal linear in field elements, thus mixing different bands [4].

We demonstrate that in multivalley 2D materials, there take place an unconventional AE effect and an AE Valley Hall effect (AVHE). We consider a transition metal dichalcogenide monolayer (Fig. 1), taking MoS_2 as an example, and show that the trigonal valley warping gives an additional component of the AE current with peculiar properties, characteristic of 2D materials (we will call this component the *warping current*). Furthermore, the Berry effect gives an unconventional acoustic drag Hall current. Moreover, the surface acoustic waves (SAWs) aspire to separate particles with opposite spins, resulting in a spin current.

A Bleustein-Gulyaev SAW with the wave vector $\mathbf{k}$ travels along the interface and creates a piezoelectric field having both the out-of-plane and in-plane components. The latter is $\mathbf{E}||\mathbf{k}$ and it acts on the 2DEG. This field drags the carriers of charge in MoS_2, resulting in the AE current. We assume that the monolayer is n-doped. Furthermore, the conduction band in each of the valleys is split by spin due to the spin-orbit interaction (SOI), as is shown in Fig. 2(a); the strength of the SOI for MoS_2 is of the order of 3 meV.

The group velocity describing the quasiclassical dynamics of a Bloch electron in the absence of an external magnetic field reads

$$\dot{\mathbf{r}} = \mathbf{v} - \dot{\mathbf{p}}\times\mathbf{\Omega}_\mathbf{p}, \tag{1}$$

where $\mathbf{v} = \partial\varepsilon_\mathbf{p}/\partial\mathbf{p}$, $\varepsilon_\mathbf{p} = \mathbf{p}^2/2m + w_\mathbf{p}$ is the electron dispersion in a given valley with account for its warping $w_\mathbf{p} = \eta C(p_x^3 - 3p_xp_y^2)$, $\eta = \pm 1$ is a valley index, C is a warping strength, and $\dot{\mathbf{p}} = e\tilde{\mathbf{E}}$ with $e<0$ the electron charge, and $\tilde{\mathbf{E}}(\mathbf{r},t) = \tilde{\mathbf{E}}e^{i\mathbf{kr}-i\omega t}/2 + \text{c.c.}$ is the overall electric field, including the piezoelectric $\mathbf{E}(\mathbf{r},t)$ and induced $\mathbf{E}^i(\mathbf{r},t)$ contributions. The origin of the induced electric field $\mathbf{E}^i(\mathbf{r},t)$ is the fluctuations of the electron density. The Berry curvature reads $\mathbf{\Omega}_\mathbf{p} = \partial_\mathbf{p}\times\langle u|i\partial_\mathbf{p}|u\rangle$ and $|u\rangle$ is a periodic amplitude of the Bloch wave function.

To describe the electron transport, we will use the Boltzmann transport equation,

$$\frac{\partial f}{\partial t} + \dot{\mathbf{p}}\cdot\frac{\partial f}{\partial\mathbf{p}} + \dot{\mathbf{r}}\cdot\frac{\partial f}{\partial\mathbf{r}} = I\{f\}, \tag{2}$$

where f is the electron distribution function, $I\{f\}$ is the collision integral. The AE current should appear as the second-order response to the external piezoelectric field.

We find the components of the current density: the AE diffusive, warping, and Hall currents. They can be written in the uniform way:

$$\begin{aligned}
\mathbf{j}^{(D)} &= \frac{e\sigma k}{2\omega}\frac{\tau}{m}\frac{\mathbf{n}}{1+(\sigma/\sigma_*)^2(1+ka)^2}E_0^2, \qquad (3)\\
\mathbf{j}^{(W)} &= e\sigma m\tau\frac{\nabla_\mathbf{n}C(\mathbf{n})\left[1+(\sigma/\sigma_*)^2(ka)^2\right]}{1+(\sigma/\sigma_*)^2(1+ka)^2}E_0^2,\\
\mathbf{j}^{(H)} &= \frac{e\sigma k}{2\omega}\frac{[\mathbf{n}\times\mathbf{\Omega}_0]}{1+(\sigma/\sigma_*)^2(1+ka)^2}E_0^2,
\end{aligned}$$

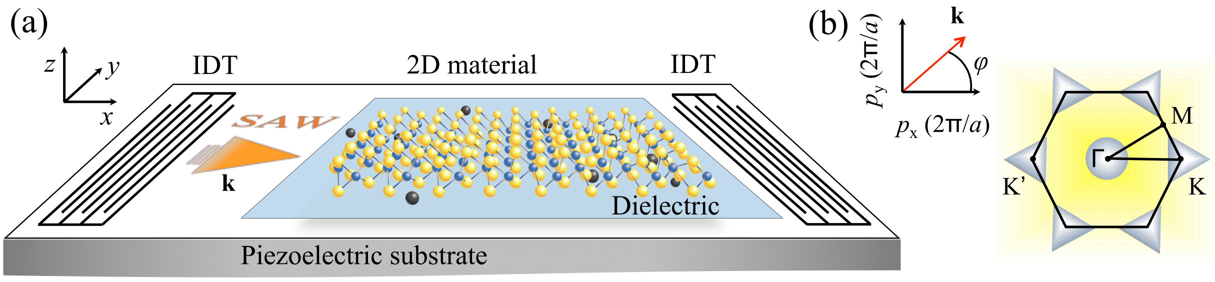

Figure 1: System schematic. (a) 2D material (MoS_2), exposed to a surface acoustic wave (SAW) with the wave vector $\mathbf{k}$. The sample lies on a layer of dielectric on a piezoelectric substrate. Two interdigital transducers (IDTs) generate and absorb the SAWs. (b) The first Brillouin zone of MoS_2 with the schematic illustration of warping.

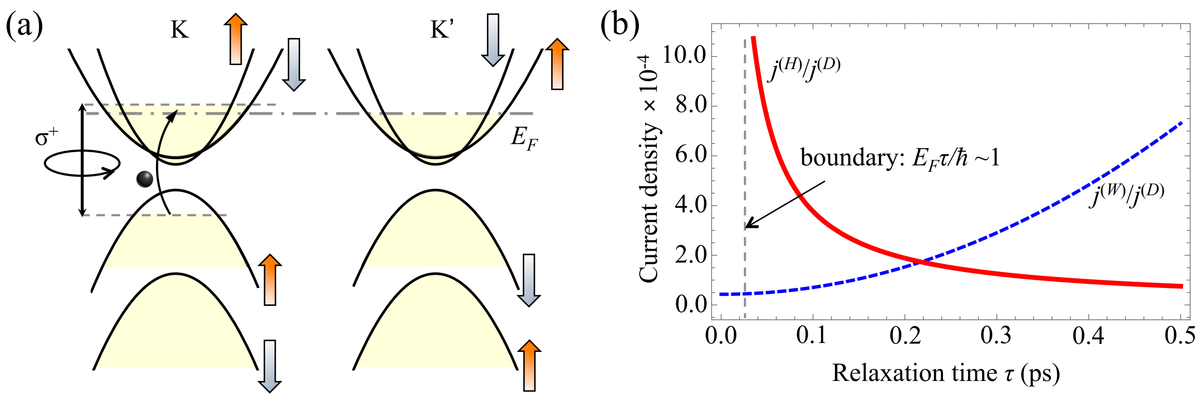

Figure 2: (a) The band structures of MoS_2 with account of the optically induced imbalance of the valley populations. Yellow shaded regions indicate the filled states. The arrows signify the directions of spin in each valley. (b) Relative magnitudes of the AE warping (dashed blue) and valley Hall (solid red) components of the current density as functions of the relaxation time at $n = 5 \times 10^{12}$ cm^{-2}.

where we choose the coordinate axes as in Fig. 1, then $\mathbf{n} = \mathbf{k}/k$, $C(\mathbf{n}) = \eta C(n_x^3 - 3n_x n_y^2)$, $\sigma_* = (\epsilon+1)s/4\pi$ and $a = (\epsilon+1)\hbar^2/(4me^2)$. The Berry curvature has an out-of-plane component $\mathbf{\Omega}_0 = (0, 0, \hbar\eta/m\Delta)$, where Δ is the band gap of the TMD monolayer. From Eqs. (3) we see that the net valley AE currents summed over the valley indexes $\eta = \pm 1$ are zero, due to the time-reversal symmetry. Hence, it should be broken to detect the valley currents. One of the possibilities to do it is to expose the sample to a circularly-polarized light with the frequency close to the band gap since the optical selection rules in 2D materials depend on η, see Fig. 2(a). Note that the warping and Hall currents depend differently on the relaxation time [see Fig. 2(b)].

In summary, we have reported on the valley acoustoelectric effect and the valley acoustoelectric Hall effect in noncentrosymmetric materials exposed to surface acoustic waves. We calculated the electric current densities and compared their magnitudes and directions of propagation with the conventional diffusive current, suggesting a way to design topologically diverse patterns of electric current and the spin current.

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2.8 Bose–Einstein condensate-mediated superconductivity in graphene

M. Sun, A. Parafilo, K. H. A. Villegas, V. M. Kovalev, I. G. Savenko

Graphene is a two-dimensional (2D) material with extremely high conductivity [1, 2]. Its chemical potential can be controlled by an external electric field; electrons and holes in graphene represent massless relativistic particles described by the 2D Dirac equation, which opens perspectives for outstanding transport characteristics and allows for the study of the interplay between relativity and superconductivity. When graphene is deposited on a substrate, it can adopt the properties of the latter such as ferromagnetism or superconductivity via the proximity effect, even though neither superconductivity nor ferromagnetism belong to the set of intrinsic properties of graphene. All this makes hybrid graphene-based structures, such as graphene–superconductor interfaces, an intense topic of research that can broadly be called *mesoscopic transport in graphene*.

Why is bare graphene not intrinsically superconducting? The primary reasons are the absence of electron–electron screening at small electron densities and the smallness of the electron density of states, which is linear in energy and thus vanishes at the Dirac point. As a consequence, electron–phonon interaction in graphene is strongly suppressed. And since the Bardeen–Cooper–Schrieffer (BCS) electron pairing below the transition temperature T_c involves basically the same matrix elements of electron–phonon interaction as the scattering matrix elements above T_c, there might be no BCS superconductivity in graphene other than that which is induced. In the meantime, pairing of particles with truly linear spectrum might result in the emergence of new collective modes or, for instance, different values of the critical magnetic fields; moreover, nontrivial (exotic) superconducting pairing states.

We proposed a non-conventional mechanism for electron–electron pairing interaction (below T_c) in graphene, beyond the acoustic phonons and impurity channels. We considered a hybrid system consisting of graphene and a 2D Bose–Einstein condensate (BEC). Excitations above the BEC, called Bogoliubov quasiparticles (or bogolons), possess properties of sound and play significant role in electron scattering processes. This leads us to surmise that graphene might acquire strong superconducting (SC) properties below T_c due to the bogolon-mediated, as opposed to the acoustic phonon-mediated, pairing of electrons. We checked this assumption and prove it valid. In this way, one state of matter (Bose condensate) can induce another state of matter (SC condensate) in neighboring graphene, avoiding a twist and securing its relativistic dispersion.

Let us consider a system consisting of a 2D electron gas in graphene and two layers containing the indirect exciton gas made of MoS_2. Such layered system can be described by the Hamiltonian

$$\mathcal{H} = \int d\mathbf{r} \int d\mathbf{R} \Psi^\dagger_{\mathbf{r}} \Psi_{\mathbf{r}} g\left(\mathbf{r} - \mathbf{R}\right) \Phi^\dagger_{\mathbf{R}} \Phi_{\mathbf{R}}, \quad (1)$$

where $\Psi_{\mathbf{r}}$ and $\Phi_{\mathbf{R}}$ are the field operators of electrons and excitons, respectively, $g\left(\mathbf{r} - \mathbf{R}\right)$ is the Coulomb interaction strength, and $\mathbf{r}$ and $\mathbf{R}$ are the in-plane coordinates of the electron and exciton center-of-mass motion, respectively. Furthermore, let us assume that the excitons are in the BEC phase, allowing us to use the model of a weakly interacting Bose gas and split $\Phi_{\mathbf{R}} = \sqrt{n_c} + \varphi_{\mathbf{R}}$, where n_c is the condensate density and $\varphi_{\mathbf{R}}$ is the field operator of the excitations above the BEC.

Since the electron spectrum in graphene consists of two nonequivalent cones with minima at the Dirac points $\mathbf{K}$ and $\mathbf{K}'$, we can define the electron field operator as

$$\Psi_{\mathbf{r}} = \frac{1}{L} \sum_{\mathbf{k},\sigma} \left(e^{i(\mathbf{K}+\mathbf{k})\cdot\mathbf{r}} c_{1,\mathbf{k},\sigma} + e^{i(\mathbf{K}'+\mathbf{k})\cdot\mathbf{r}} c_{2,\mathbf{k},\sigma} \right), \quad (2)$$

where $c_{\alpha,\mathbf{k},\sigma}$ are electron annihilation operators in which $\alpha = 1, 2$ is the valley index and

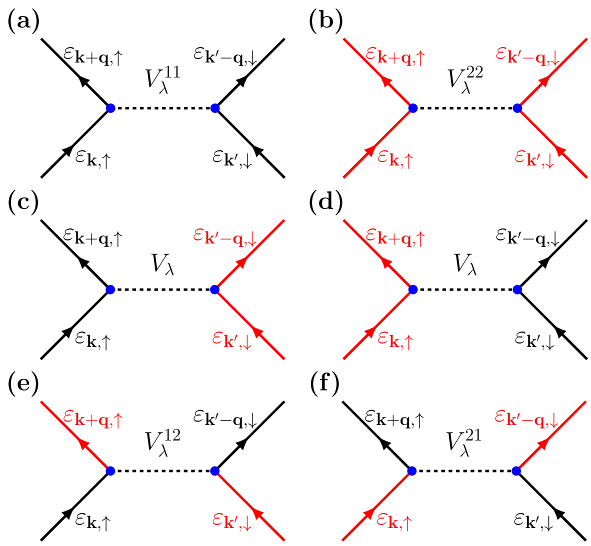

Figure 1: Feynman diagrams illustrating intravalley (a,b) and intervalley (c–f) pairings in accordance with the Hamiltonian (1). Red and black lines describe electrons in the K and K' valleys, respectively.

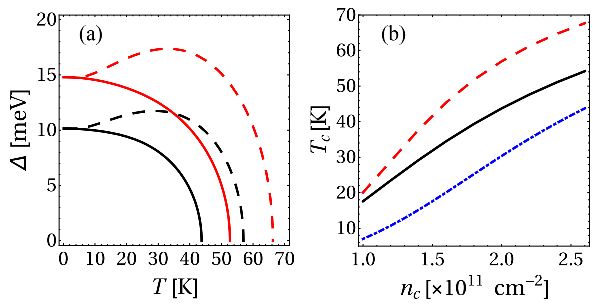

Figure 2: (a) Temperature dependence of the SC gap for bogolon-pair-mediated process. (b) Critical temperature of the SC transition as a function of condensate density for bogolon-pair-mediated interaction.

$\sigma =\uparrow,\downarrow$ is the electron spin projection. We come up with the terms $\mathcal{H}_1$ and $\mathcal{H}_2$, which describe single-bogolon (1b) and bogolon-pair (2b)-mediated processes. Integrating out the bogolon degrees of freedom by using a standard procedure based on the Schriffer–Wolff transformation over the terms in the Hamiltonian, we find an effective Hamiltonian for 1b or 2b pairings. The corresponding Feynman diagrams for two-electron scattering are plotted in Fig. 1. They give relatively high value for the superconducting gap and the critical temperature of superconducting transition (Fig. 2).

In summary, we studied the bogolon-mediated interaction of electrons in graphene in the vicinity of a two-dimensional Bose-condensed dipolar exciton gas. We developed the BCS-like bogolon-mediated electron pairing theory and calculated the critical temperature of the superconducting transition in graphene, and compared it with the temperature of the BKT transition. We showed that bogolon-pair-mediated interaction allows one to solve the problem of the smallness of the density of states in two-dimensional Dirac materials with linear spectrum at small momenta.

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2.9 Interplay between spin-orbit coupling and Van Hove singularity in the Hund's metallicity of Sr_2RuO_4

Hyeong Jun Lee, Choong H. Kim, Ara Go

We investigate the role of spin-orbit coupling and van Hove singularity in the dynamical properties of SRO, which becomes prominent at zero and very low temperature by means of density functional theory plus dynamical mean-field theory with an exact diagonalization solver. We examine the crossover between a Fermi liquid and a Hund's metal for a wide range of temperatures and Hund's coupling. In the absence of doping, we confirm that the Fermi liquid persists at zero temperature even with nonzero Hund's coupling. The freezing-moment mechanism suggests that thermal fluctuations lead to a suppression of the Fermi liquid phase and promotes the Hund's metallicity with incoherence. We show that the van Hove singularity is an additional key ingredient to drive the suppression at very low temperature by observing doping dependence of the freezing or long-lived paramagnetic moments. The role of spin-orbit coupling is marked by an amplified van Vleck contribution of spin susceptibility, significantly promoting the Hund's metallicity. Combined with the strong doping dependence of Hund's metallicity, we propose a control of the van Hove singularity in SRO (ttgf) is enhancing Hund's metallicity of the SRO, which can be achieved by doping and even possibly by strain.

We first perform calculation for the bare SRO to test whether the ED solver can reproduce well-known consensus in this system. Based on the self-energy, the d_{xy} orbital is more strongly correlated in comparison to the other two t_{2g} orbitals. Since the d_{xy} orbital experiences a drastic change in correlations over temperature as well as the Hund's coupling, its self-energy $\Sigma_{xy}(i\omega)$ is a good measure for identifying whether it follows Fermi liquid behavior or not. We present the power exponent of the imaginary part of the self-energies in Fig. 1(a) as Hund's coupling and temperature vary.

Development of the long-lived paramagnetic moment (or so-called moment freezing) can be observed in the related magnetic susceptibility as a non-vanishing long-time correlator. The long-time correlator is defined as

$$\chi^S_{zz}(\tau = \beta/2) = \langle \hat{S}_z(\beta/2)\hat{S}_z \rangle,$$

where β is the inverse temperature, and $\hat{S}_z$ is the z-component of the total angular momentum operator. To examine the origin of the power reduction in SRO, we compute the magnetic susceptibility as displayed in Fig. 1(b). We observe a clear similarity of the T- and J_H-dependencies between the two quantities in Fig. 1 (a) and (b). When the exponent indicates Fermi liquid, the long-time correlator is vanishingly small.

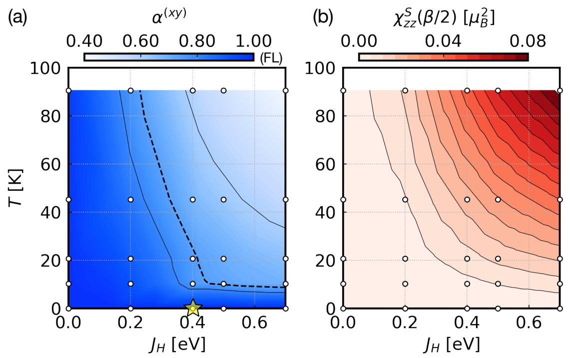

Figure 1: (a) Power exponent α of the imaginary part of the Matsubara self-energy and (b) long-time correlator $\chi^S_{zz}(\tau = \beta/2)$ in the T-J_H plane. The dashed line in (a) denotes the crossover between Fermi liquid and Hund's metal regimes, and the yellow star marks a realistic value of J_H for SRO.

We obtain power exponent α by fitting the self-energies to $\mathrm{Im}\Sigma(i\omega_n) \sim \omega_n^\alpha$ with the two lowest values of ω_n. The linear power of the self-energy (marked in blue in Fig. 1(a)) with respect to the Matsubara frequency, i.e. $\mathrm{Im}\Sigma_{xy}(i\omega) \sim \omega$, indicates that the system is in the Fermi liquid phase. This phase is stable over the entire range of temperature that we can access when Hund's coupling is zero. We define the Fermi liquid temperature T_{FL} for a given J_H as the temperature whose corresponding value of α equals the α at $T = 25$ K for $J_H = 0.4$ eV. To present how the Fermi liquid regime evolves as a function of J_H, we mark $T_{\rm FL}$ with a dashed line in Fig. 1(a). $T_{\rm FL}$ decreases once Hund's coupling is turned on, but the Fermi liquid ground state persists up to $J_H = 0.7$ eV. At $J_H = 0.4$ eV, which is believed to be a typical Hund's coupling strength in SRO, the linear power seems to hold below 10 K in our result. This scale is comparable with previous experimental results from resistivity curves.

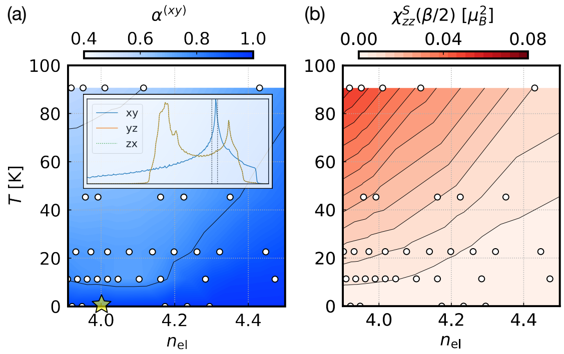

Figure 2: Doping dependence around the van Hove singularity. (a) Power exponent of the imaginary part of the Matsubara self-energy and (b) long-time correlator $\chi^S_{zz}(\tau = \beta/2)$ in the T-$n_{\rm el}$ plane. Inset: Projected density of states on t_{2g} for the non-interacting case. Vertical dotted lines denote the Fermi level when $n_{\rm el} = 4$ and 4.35 around the VHS of the d_{xy} band.

We have observed that Hund's coupling suppresses the Fermi liquid regime at ttgf, showing consistent behavior with the long-time correlator. This power exponent deviation and $T_{\rm FL}$ reduction in SRO are reminiscent of the J_H-induced spin-freezing crossover in the three-band model at ttgf. However, there is a prominent difference upon electron doping due to the VHS of SRO. Previous model calculations for the Bethe lattice showed that Fermi liquid behavior is enhanced by electron doping on top of ttgf, while earlier DFT+DMFT works focused on the Hund's metallicity of bare SRO. In SRO, though, there is a nontrivial doping dependence of the power exponent. In Fig. 2, we compare the power exponent from Σ_{xy} and the long-time correlator for electron-doped cases. Unlike the ttgf case shown in Fig. 1, the two quantities reveal a quantitatively distinct behavior for $n_{\rm el} > 4$ (where $n_{\rm el}$ is electron occupancy). Here, $T_{\rm FL}$ becomes minimal around $n_{\rm el} \sim 4.1$, while the long-time correlator monotonically decreases in the regime shown in Fig. 2. This can be attributed to the electronic structure of SRO that has a VHS slightly above the Fermi level in the absence of doping. This supports that a mechanism separate from spin-freezing leads the power deviation. The VHS strongly suppresses hybridizations and amplifies the correlation effect delivered to the self-energy. The lowest $T_{\rm FL}$ is achieved when a Lifshitz transition appears and the VHS is expected to cross the Fermi level. Its doping concentration is, however, a bit less than one previously reported in experiments and in a non-interacting case. The lowest $T_{\rm FL}$ moves to a higher $n_{\rm el}$ if SOC is turned off; this originates from the VHS and the enhanced magnetic fluctuations by SOC, which will be discussed in more detail later in this Letter.

In summary, we performed DFT+DMFT calculations with an exact diagonalization solver on SRO. Considering the rotationally invariant Slater–Kanamori interaction as well as spin-orbit coupling, we constructed a comprehensive phase diagram on the $T - J_H$ plane by extracting power exponents of the self-energy. The ground state is a Fermi liquid, and the system enters the Hund's metal regime as the temperature increases, with Hund's coupling suppressing the Fermi liquid temperature. We identified the particular parameter set that reproduces experimentally observed spectral functions. The ground state of SRO turned out to be very close to the Hund's metal regime in the phase diagram, reflecting its correlated nature. We then applied electron doping to study how the VHS affects the correlated metal, and found that the VHS extends the Hund's metal regime, enhancing the scattering rate of the electrons, whereas the long-time correlator weakens as the system is doped.

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2.10 Vestiges of Topological Phase Transitions in Kitaev Quantum Spin Liquids

Ara Go, Jun Jung, Eun-Gook Moon

We investigate signatures of topological quantum phase transitions (TQPTs) between the Z_2 quantum spin liquids (QSLs). In two spatial dimensions, Z_2 QSLs and their TQPTs are only well defined at zero temperature ($T = 0$), and it is imperative to clarify their observable signatures under nonzero temperatures. Here, we present the vestiges of TQPTs between Z_2 QSLs with Majorana fermions in terms of thermal Hall conductivity κ_{xy} at nonzero temperatures. The κ_{xy}/T shows characteristic temperature dependences around TQPTs. We argue that an exponential upturn near $T = 0$ and the peak of κ_{xy}/T around massive excitation energy are observable smoking-gun signals of the TQPTs. Quantum critical fan-shape temperature dependences are uncovered across TQPTs. We also perform the parton mean-field analysis on a modified Kitaev model with next-nearest neighbor interactions finding TQPTs between the phases with different Chern numbers and their vestiges self-consistently. We discuss the implication of our results to the recent experiments in α-$RuCl_3$.

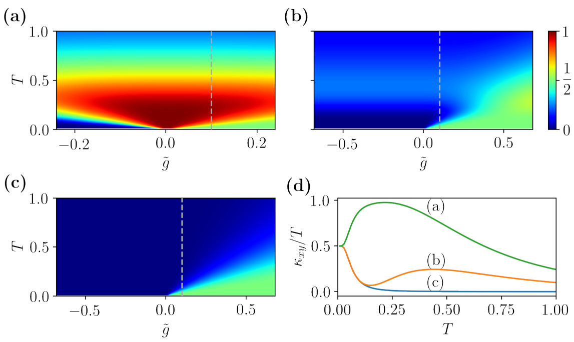

Figure 1: $\kappa_{xy}^{\text{edge}}/T$ near TQPTs between the phases with $\nu = 0$ and $\nu = 1$. The units of $\kappa_{xy}^{\text{edge}}/T$ and T are $(\pi/6)(k_B^2/\hbar^2)$ and $\Delta_1/2$, respectively. The smallest gap depends on $|\tilde{g}|$ linearly, ($\Delta_4 = \Delta_1|\tilde{g}|$). $\tilde{g} > \tilde{g}_c$ is for the phases with $\nu = 1$, and its false color representations of $\kappa_{xy}^{\text{edge}}/T$ are given in (a)-(c). (d) $\kappa_{xy}^{\text{edge}}/T$ at $\tilde{g} = 0.1$ (marked by dashed lines in (a)-(c)).

We first construct an edge theory of a gapped Kitaev QSL to observe how the thermal Hall conductivity evolves in different QSLs as temperature increases. The energy dispersion of a chiral mode is well defined in the interval $\epsilon_n(k_x) \in (0, \Delta_n)$ if $\nu_n \neq 0$. Defining an edge thermal current, $J_e(T) = \sum_n \int \frac{dk_x}{2\pi} v_n(k_x)\epsilon_n(k_x) f[\epsilon_n(k_x)]$ with a velocity of the mode (v_n) and the Fermi distribution function (f), the thermal Hall conductivity divided by temperature is obtained,

$$\frac{\kappa_{xy}^{\text{edge}}}{T} = \sum_n \nu_n \Big\{ \frac{\pi}{12} - \frac{1}{2\pi T^3} \int_{\Delta_n}^{\infty} \frac{\epsilon^2 e^{\epsilon/T}}{(1+e^{\epsilon/T})^2} d\epsilon \Big\}. \quad (1)$$

We use the units ($k_B = \hbar = 1$). The edge current becomes exact when bulk bands are flat (localized). Its quantization is obvious in the zero temperature limit ($\kappa_{xy}^{\text{edge}}/T \to \nu\pi/12$).

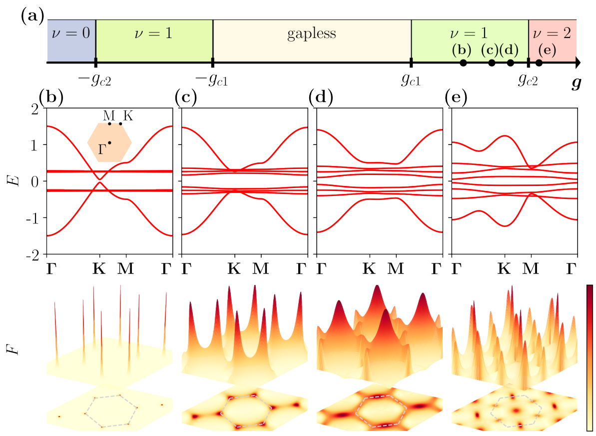

Figure 2: (a) Phase diagram of $H_{\text{tot}} = H_K + g(H_{I,A} + H_{I,B})$ with parton mean-field analysis. Band structure along the high symmetry line for few selected values of g, (b) g=1.6, (c) g=1.9, (d) g=2.1, and (e) g=2.3. The corresponding Berry curvature in the momentum space are given below the band structure. The first Brillouin zone is marked by dashed lines in the projection.

Near a TQPT, we introduce a parameter $\tilde{g}$ to describe a gapped Kitaev QSL with ν ($\tilde{g} < \tilde{g}_c$) and the one with ν+1 ($\tilde{g} > \tilde{g}_c$). A critical value $\tilde{g}_c$ is set to be zero hereafter. We assume the lowest energy gap has the dependence $\Delta_4 \propto |\tilde{g}|$ near the TQPT and the corresponding mode has a linear dispersion relation, which is supported by our parton mean-field analysis below. Generalization to generic TQPTs is straightforward. At the quantum critical point, using the edge theory Eq. (1) may be subtle, but as shown below, the edge theory results are well matched with the bulk theory calculations. Ignoring $\tilde{g}$ dependences of the bigger energy gaps ($\Delta_{1,2,3}$), we illustrate $\kappa_{xy}^{\text{edge}}/T$ for TQPTs between $\nu = 0$ and $\nu = 1$ in Fig. 1. Striking temperature dependences appear at nonzero temperatures, characterized by the structures of (ν_n, Δ_n), as shown in Figs 1(a)–1(c). For detailed conditions of (ν_n, Δ_n), we refer the readers to [1].

For more realistic analysis, we perform a parton mean-field calculation for a spin Hamiltonian,

$$\begin{aligned} H_{I,A} &= -\frac{K}{2} \sum_{\bigtriangledown,ijk} S_i^x S_j^y + S_j^y S_k^z + S_k^z S_i^x \\ H_{I,B} &= -\frac{K}{2} \sum_{\triangle,lmn} S_l^x S_m^y + S_m^y S_n^z + S_n^z S_l^x . \end{aligned}$$

The summations over $\bigtriangledown, \triangle$ corresponds to summations around a different sublattice point in a unit cell. The solution is presented in Fig. 2. We find three different phases separated by $g_{c_1} \sim 1.05$ and $g_{c_2} \sim 2.25$ for $g > 0$. For $g < 0$, only the Chern numbers of $\vec{b}$ Majorana fermions are opposite to the ones at $|g|$.

The bulk thermal Hall conductivity is computed by using the conventional formula,

$$\frac{\kappa_{xy}^{\text{bulk}}}{T} = -\frac{1}{T^2} \int d\epsilon\, \epsilon^2 \frac{\partial f(\epsilon, T)}{\partial \epsilon} \sum_{\mathbf{k}, \varepsilon_n(\mathbf{k}) < \epsilon} F_n(\mathbf{k}),$$

where the $\mathbf{k}$ summation runs over the first Brillouin zone and $\varepsilon_n(\mathbf{k})$ is the nth energy eigenvalue of the mean-field Hamiltonian. At $T \to 0$, $\kappa_{xy}^{\text{bulk}}/T$ is quantized as $\nu\pi/12$. Our calculations are asymptotically exact at low temperatures and naturally become uncontrolled at temperatures higher than the gap energy scale.

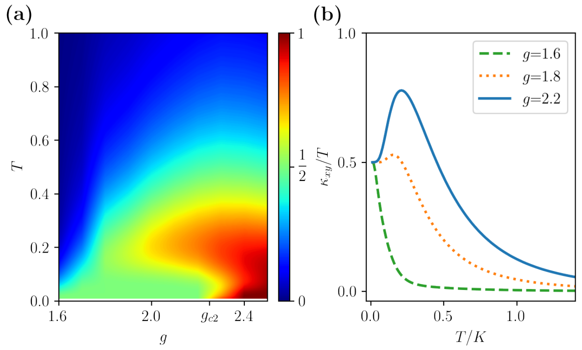

Figure 3: (a) False color representation of κ_{xy}/T on $g - T$ plane with $g_{c2} \sim 2.25$. (b) T dependence of κ_{xy}/T for g= 1.6 (dashed), 1.8 (dotted), 2.2 (plain). The unit of κ_{xy}/T is the same as in Fig. 1

In Fig. 3(a), the density plot of $\kappa_{xy}^{\text{bulk}}/T$ is illustrated. Qualitative dependences on T and g are similar to Fig. 1. For example, the critical-fan shape appears as in Figs. 1(b) and 1(c) near g_{c2}, but away from g_{c2}, it is more distorted than Fig. 1 because higher energy bands depend on g and have dispersive spectrums. In Fig. 3(b), we plot temperature dependences of $\kappa_{xy}^{\text{bulk}}/T$ for different values of g. For $g = 1.6$, $\kappa_{xy}^{\text{bulk}}/T$ monotonically decreases as the temperature rises, but for $g = 2.2$, nonmonotonic temperature dependences appear with a peak around $T/K \sim \Delta_4$ and, for $T \ll \Delta_4$, the upturn temperature dependence is exponential. The bigger band gaps $\Delta_{1,2}$ are in an order of magnitude larger than Δ_4, and the Chern number vector is $\vec{\nu} = (1, 1, 0, -1)$. The qualitative matching between $\kappa_{xy}^{\text{edge}}/T$ and $\kappa_{xy}^{\text{bulk}}/T$ is one sanity check of our analysis.

In conclusion, we study the vestiges of TQPTs in Kitaev QSLs by using path-integral and parton mean-field analysis. Around TQPTs, characteristic temperature dependences of κ_{xy}/T are obtained, including quantum-critical fan-shape dependences, and we provide smoking-gun signatures of TQPTs which may be tested in future experiments.

[1] Phys. Rev. Lett. **122**, 147203 (2020).

2.11 Probing bulk topological invariants using leaky photonic lattices

D. Leykam, D. A. Smirnova

Analogies between condensed matter physics and other fields including photonics have been a powerful source of inspiration for various devices such as photonic crystals, optical waveguides, and lasers. But these analogies are typically inexact and based on certain approximations.

For example, topological properties of electronic systems are determined by topological invariants defined as integrals of some effective field strength over all the occupied bands, i.e. modes with energies below the Fermi level. On the other hand, bosonic systems do not naturally fill their energy bands; they either condense into the ground state or are driven at some specific energy. This makes it more difficult to relate topological invariants of bosonic systems to robust quantized observables such as the Hall conductivity of electronic systems. Hence, measurement of bulk topological invariants of bosonic systems remains challenging, typically requiring Bloch band tomography.

We have proposed a novel approach for emulating the Fermi levels of electronic systems using non-interacting bosons in certain non-Hermitian lattices subject to radiative losses. By controllably filling bands of interest, one can directly measure their quantized topological invariants. Most importantly, in contrast to existing approaches requiring laborious tomographic reconstruction of the eigenstates, our method does assume a perfectly periodic lattice and is also applicable to finite and disordered systems, enabling the study of topological properties in real space.

Our starting point is the Schrödinger equation, which describes propagation in many kinds of linear wave media,

$$i\partial_t \psi(\boldsymbol{r},t) = [-\frac{1}{2m}\nabla^2 + V(\boldsymbol{r})]\psi(\boldsymbol{r},t), \qquad (1)$$

where t is the evolution time, m is the wave effective mass, and $V(\boldsymbol{r})$ is a localised potential profile. For example, Eq. (1) is equivalent to the paraxial equation under the replacements $t \to z$, $\boldsymbol{r} = (x,y)$, $m \to k_0$, and $V(\boldsymbol{r}) \to -k_0 \delta n(\boldsymbol{r})/n_0$, where z is the propagation distance, $k_0 = 2\pi n_0/\lambda$ is the wavenumber, n_0 the ambient refractive index, λ is the free space wavelength, and $\delta n(x)$ is the deviation of the refractive index from n_0.

Usually Eq. (1) is analyzed in terms of its proper modes $\psi(\boldsymbol{r},t) = \phi(\boldsymbol{r})e^{-iEt}$, where the propagation constant E is real. In the following the improper “leaky” modes with complex propagation constants $E+i\gamma$ will play a crucial role. Leaky modes are obtained by assuming a finite lattice and outgoing wave boundary conditions. For example, in the one-dimensional case $\boldsymbol{r} = x$ we assume $V(x)$ only varies for $x \in (0,L)$. Outside the lattice $V(x) \to V_0$ and $\phi(x) \propto \exp(\pm\xi x)$, where

$$\xi = \pm\sqrt{2m(V_0 - E - i\gamma)}. \qquad (2)$$

is the transverse localization length. Leaky modes are obtained by solving the eigenvalue problem

$$\begin{aligned}&(E+i\gamma)\phi + \frac{1}{2m}\partial_x^2\phi - V(x)\phi = 0, \quad x \in (0,L)\\ &\partial_x\phi(0) - \xi\phi(0) = 0,\\ &\partial_x\phi(L) + \xi\phi(L) = 0.\end{aligned}$$

When the lattice potential comprises weakly-coupled waveguides one can apply coupled mode theory to reduce the continuum Schrödinger equation to a discrete nonlinear eigenvalue problem of the form

$$\left(\hat{H} + \xi\hat{B} + \xi^2\hat{S}\right)\phi = 0, \qquad (3)$$

where $\hat{H}$ encodes the energies of the individual waveguide modes and the coupling between them, $\hat{B}$ the overlap of the waveguide modes with the boundary of the domain, and $\hat{S}$ the overlap between different modes. This eigenvalue problem can be solved for the localization length ξ, from which the modal energies are obtained as $E = V_0 - \xi^2/(2m)$. When $\mathrm{Re}(E) > V_0$

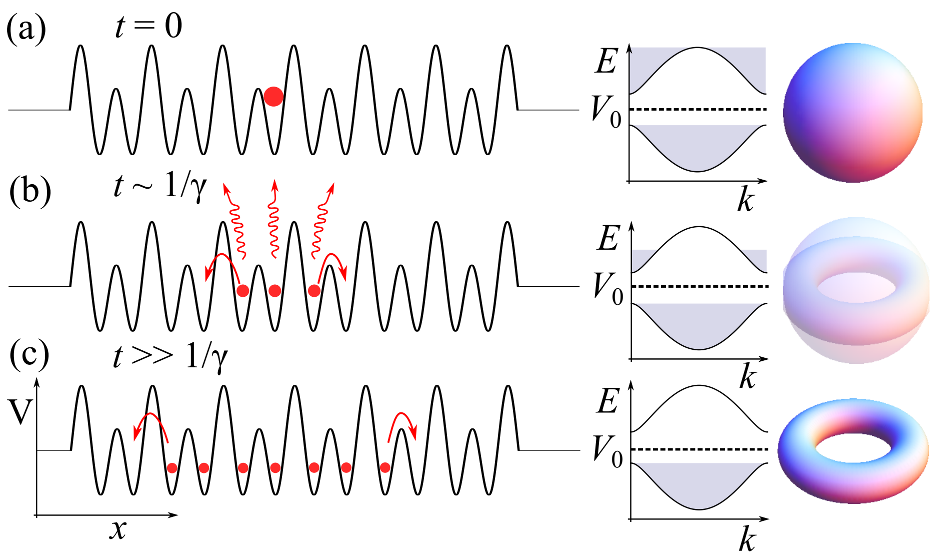

Figure 1: Schematic of method to measure topological invariants using leaky lattices. (a) A spatially-localised excitation (red circle) excites all bands of the lattice and is hence insensitive to the individual bands' topology. (b) Dynamics: The excitation diffracts through the lattice, while leaky modes of the bands with energies $E > V_0$ have a finite lifetime and radiate their energy. (c) At times exceeding the leaky mode lifetime $1/\gamma$ only bound bands remain populated and their topology is imprinted on time-independent observables of the (still-diffracting) field.

the modes become leaky and radiate energy to $r \to \infty$, acquiring a finite decay rate $\mathrm{Im}(E)$.

The cutoff energy between bound and leaky quasi-normal modes is analogous to the electronic Fermi level; all modes above this energy dynamically decay, resembling a form of evaporative cooling. By controlling the cutoff energy one can achieve controlled filling of a desired number of bands, as illustrated schematically in Fig. 1. In effect, an arbitrary initial field profile is projected onto the bound bands, enabling direct measurement of their bulk topological invariants.

We demonstrated our scheme using numerical simulations of the Su-Schrieffer-Heeger and Haldane models, as well as light propagation in a slab waveguide array. Our models can also be implemented using existing platforms for topological lattices, such as deep waveguide arrays or photonic crystals. In the former, one can introduce radiative losses using auxiliary waveguide arrays weakly coupled to the sites of the lattice of interest. For the latter, one could embed the topological photonic crystal within an appropriately-designed photonic crystal environment.

Leaky lattices also promise to be a flexible platform for exploring related topics including non-Hermitian systems and non-Hermitian topological phases. Our models based on the non-interacting Schrödinger equation are applicable to other bosonic wave systems including acoustics and Bose-Einstein condensates, where the phenomena we have discussed may be further enriched by effects such as spin-orbit coupling and inter-particle interactions.

[1] D. Leykam, D. A. Smirnova Nature Physics, **17**, 632 (2021).

2.12 Probing band topology using modulational instability

D. Leykam, E. Smolina, A. Maluckov, S. Flach, D. A. Smirnova

Topologically nontrivial photonic bands can now be combined with appreciable mean-field nonlinear interactions in a variety of experimental platforms. Nonlinear topological photonic systems are of growing interest not only due to their ability to host novel phenomena with no analogue in electronic topological materials, but also their potential device applications such as novel types of lasers, optical isolators, and frequency combs. Existing theoretical studies have focused on the use of nonlinearities to control the propagation of wavepackets accessible in the linear limit, using effects such as the self-focusing, soliton formation, and nonlinearity-induced coupling between bulk and edge modes. However, as complex nonlinear wave systems are typically sensitive to perturbations, precise control over excitation conditions is required and the robustness of these effects to disorder remains an open question, potentially limiting their utility.

We have investigated how topologically nontrivial states of light may emerge spontaneously from simple plane-wave-like initial state in nonlinear systems via the process of modulational instability. The underlying mechanism is the energy-dependent parametric gain provided by the modulational instability, which allows one to fill a single Bloch band starting from a single eigenstate. As well as providing a mechanism for sculpturing novel structured light fields, the modulational instability provides a simple way to measure the bulk topological invariants of bosonic wave systems, which is generally a difficult task unless one knows their eigenstates *a priori*, performs time-consuming Bloch band or Berry curvature tomography, or relies on the bulk-edge correspondence.

We considered the two-dimensional nonlinear Schrödinger equation describing the nonlinear (mean-field) wave propagation dynamics in photonic lattices,

$$i\partial_t \psi_{\boldsymbol{r}} = (\hat{H}_L + \hat{H}_{NL})\psi_{\boldsymbol{r}}, \qquad (1)$$

where $\hat{H}_L$ and $\hat{H}_{NL}$ are linear and nonlinear parts of the Hamiltonian, respectively, and $\boldsymbol{r} = (x, y)$ indexes the lattice sites. As an example, we take $\hat{H}_L$ to be the chiral-π-flux model illustrated Fig. 1(a), a two band tight binding model for a Chern insulator on a square lattice comprising two sublattices a and b, with $\psi_{\boldsymbol{r}} = (\psi_{\boldsymbol{r}}^{(a)}, \psi_{\boldsymbol{r}}^{(b)})^T$. For the nonlinear part of the Hamiltonian $\hat{H}_{NL}$ we assume an on-site Kerr-like nonlinearity of the form

$$\hat{H}_{NL}\psi_r^{(j)} = \Gamma f(|\psi_{\boldsymbol{r}}^{(j)}|^2)\psi_{\boldsymbol{r}}^{(j)}, \qquad (2)$$

where Γ is the nonlinear interaction strength, f is the nonlinear response function, and $j = a, b$ indexes the sublattices. The linear Bloch wave eigenstates of $\hat{H}_L$ can be continued as nonlinear Bloch waves, which are solutions of the nonlinear eigenvalue problem $E(\boldsymbol{k})\phi(\boldsymbol{k}) = (\hat{H}_L(\boldsymbol{k}) + \hat{H}_{NL})\phi(\boldsymbol{k})$. Their stability can be studied by considering the time evolution of small perturbations $p \ll 1$, i.e. $\psi(t) = (\phi(\boldsymbol{k}_0)e^{i\boldsymbol{k}_0\cdot\boldsymbol{r}} + p(\boldsymbol{k}, t)e^{i\boldsymbol{k}\cdot\boldsymbol{r}})e^{-iEt}$, and linearizing the equations of motion. Perturbation modes with eigenvalues λ with a positive imaginary part are linearly unstable.

Figure 1(b) plots the growth rate of the most unstable perturbation mode as a function of Γ and Δ, the potential imbalance between the two sublattices, which tunes between trivial and nontrivial phases. For weak nonlinearities Γ we observe behaviour qualitatively similar to the scalar nonlinear Schrödinger equation: Bloch waves at the band edge exhibit a long wavelength instability under self-focusing nonlinearity, i.e. when $\Gamma m_{\text{eff}} < 0$, where $m_{\text{eff}} = \Delta - 4J_2$ is the wave effective mass at $\boldsymbol{k}_0$. Interestingly, a second long wavelength instability occurs for stronger nonlinearities in the vicinity of the stable line $\Gamma I_0/2 = -m_{\text{eff}}$. This critical line occurs when the nonlinearity-induced potential closes the band gap and corresponds to a transition from an exponential instability at weak Γ to an oscillatory instability at strong Γ. The instability spectrum does not just depend on the energy eigenvalue dispersion, but is also sensitive to the band topology.

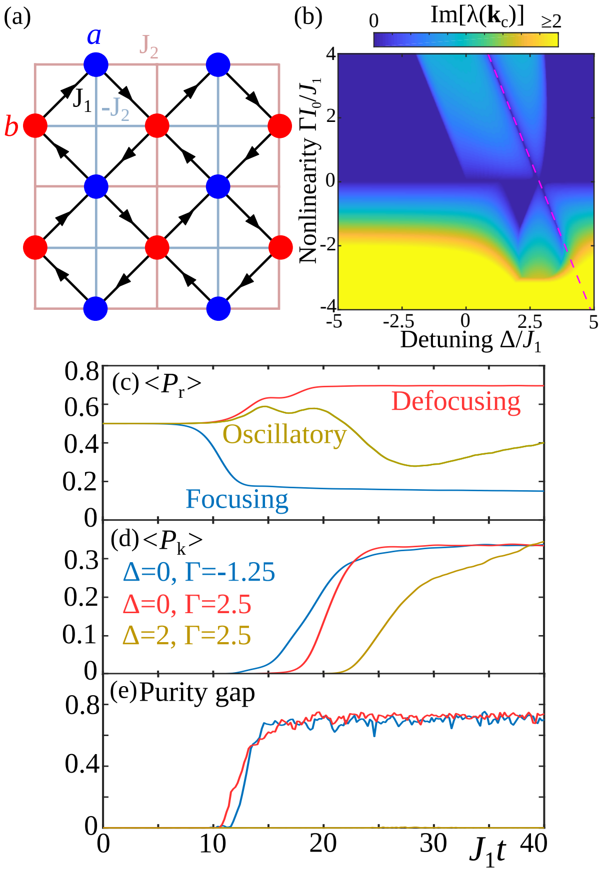

Figure 1: (a) Schematic of the chiral-π-flux model, consisting of two sublattices (a, b) with detuning Δ and inter- (intra-) sublattice couplings J_1 (J_2). (b) Instability growth rate. Purple dashed line marks the nonlinearity-induced gap closure, and the nonlinear Bloch wave is stable in the dark blue areas. (c,d,e) Long time instability dynamics in the different instability regimes: focusing exponential (blue), defocusing exponential (red), and oscillatory instability (brown). (c) Real space participation number. (d) Fourier space participation number. (e) Purity gap.

We also carried out out numerical simulations of Eq. (1) to study the modulational instability beyond the initial linearized dynamics. To characterize the complex multi-mode dynamics, we computed three summary observables: (i) The real space participation number P_r, which measures the fraction of strongly excited lattice sites, (ii) the Fourier space participation number P_k, which measures similarly the fraction of excited Fourier modes, and (iii) the field polarization direction $\hat{\boldsymbol{n}}_\psi(\boldsymbol{k})$, which exhibits singularities sensitive to the band topology. We averaged each observable over an ensemble of random small perturbations to the Bloch wave initial state. The average polarization $\langle \hat{\boldsymbol{n}}_\psi(\boldsymbol{k}) \rangle$ in general describes a mixed state with $n_\psi^2 = \langle \hat{\boldsymbol{n}}_\psi(\boldsymbol{k}) \rangle \cdot \langle \hat{\boldsymbol{n}}_\psi(\boldsymbol{k}) \rangle < 1$. When $n_\psi^2 > 0$ for all $\boldsymbol{k}$, i.e. the "purity gap" $\min_{\boldsymbol{k}}(n_\psi^2)$ remains open, the wave field is characterized by a quantized Chern number.

Fig. 1(c,d,e) illustrates the long time dynamics for different choices of parameters. When the instability is real we observe the emergence of a nonzero purity gap and the development of a quasi-steady-state with a well-defined Chern number, corresponding to the linear band's Chern number. On the other hand, under the oscillatory instability the purity gap remains negligible due to strong nonlinear mixing between the different Bloch bands.

Since the instability timescales appear to be shorter than the wave thermalization time, these effects should be experimentally observable in nonlinear waveguide arrays, Bose-Einstein condensates in optical lattices, or exciton-polariton condensates. While we focused on the chiral-π-flux model, we have observed similar behaviour in other topological tight binding models. Lattices with a larger band flatness typically exhibit emergence of a purity gap and well-defined Chern number for a wider range of nonlinearity strengths. It will be interesting to generalize our findings to periodically-driven Floquet systems, where perfectly flat topological bands have been demonstrated.

[1] D. Leykam, E. Smolina, A. Maluckov, S. Flach, D. A. Smirnova, Physical Review Letters, **126**, 073901 (2021).

2.13 Stochastic thermodynamics of inertial-like Stuart-Landau dimer

J.-W. Ryu, A. Lazarescu, R. Marathe, J. Thingna

Our first main aim is to understand the effects of the inertial-like term on the phase diagram for the nonlinear oscillator model and explore how synchronisation affects the work and heat exchanges which characterise it as a thermodynamic machine. Similar to the inertial Kuramoto model, we find that due to the inertia-like term the zero-temperature phase diagram develops bistability leading to a coexistence of coherent and incoherent limit cycles. Secondly, we build a stochastic thermodynamics framework and show that the thermodynamic observables (heat and work) depend strongly on the physical interpretation of the dynamical equations being analyzed.

The Stuart-Landau oscillator (SLO) is a prototypical system exhibiting Hopf bifurcation and limit cycle oscillations that can reveal universal features of many practical systems. We introduce and study the inertial-like Stuart–Landau dimer, comprising of two coupled SLOs, and investigate the effects of the inertial-like term on its phase diagram. We first extend the standard damped Stuart-Landau model which is a model for Hopf bifurcation and limit cycle oscillations to the underdamped regime accounting for the inertial-like term and incorporating Gaussian white noise whose strength obeys the Fluctuation-dissipation relation. Two oscillators of the dimer synchronize in specific parameter regimes and the presence of noise indicates that the synchronizing model is connected to thermal reservoirs. A potentially useful and equivalent way to rewrite these equations is to use the complex notation $z_j = x_j + iy_j (j = 1, 2)$ which yields the following compact expressions:

$$m\ddot{z}_1 = \left(R + i\gamma\omega_1 - |z_1|^2\right) z_1 \\ -\gamma\dot{z}_1 + k(z_2 - z_1) + \xi_1, \quad (1)$$

$$m\ddot{z}_2 = \left(R + i\gamma\omega_2 - |z_2|^2\right) z_2 \\ -\gamma\dot{z}_2 + k(z_1 - z_2) + \xi_2, \quad (2)$$

where ω_j is mass and frequency of the oscillators, R is strength of the nonlinear potential, k is strength of the spring coupling between oscillators, and γ is Stokesian damping coefficient. The random noise $\xi_{1,2}$ are Gaussian with zero mean and $\langle \xi_l^\alpha(t) * \xi_j^\beta(t') \rangle = 2\gamma_j k_B T_j \delta(t-t')\delta_{\alpha,\beta}\delta_{l,j}$, where $\langle\cdot\rangle$ represents the ensemble average over the noises.

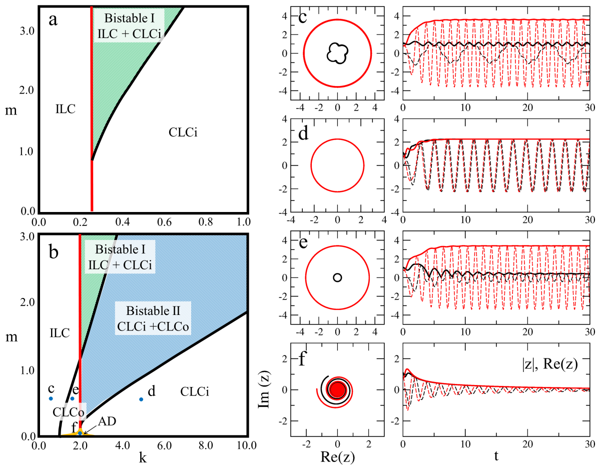

Figure 1: Phase diagrams when (**a**) $\Delta\omega = \omega_2 - \omega_1 = 0.5$ and (**b**) $\Delta\omega = 4.0$. The coexistence of incoherent and coherent limit cycles is shaded in green (bistable I) whereas the coexistence of different types of coherent limit cycles is in blue (bistable II). Trajectories on the complex plane and time series of the two oscillators when (**c** and **g**: ILC) (k, m) = (0.5, 0.5), (**d** and **h**: CLCi) (5.0, 0.5), (**e** and **i**: CLCo) (1.5, 0.5), and (**f** and **j**: AD) (2.0, 0.1) [1].

In the zero-temperature limit, wherein the oscillators experience no stochastic force but are damped, we find that the phase diagram of our underdamped Stuart-Landau model shows a rich complex behavior, an incoherent limit cycle (ILC), amplitude death (AD), and an in-phase coherent limit cycle (CLCi), an out of phase coherent limit cycle (CLCo), and bistable regimes, as shown in Fig. 1 [1].

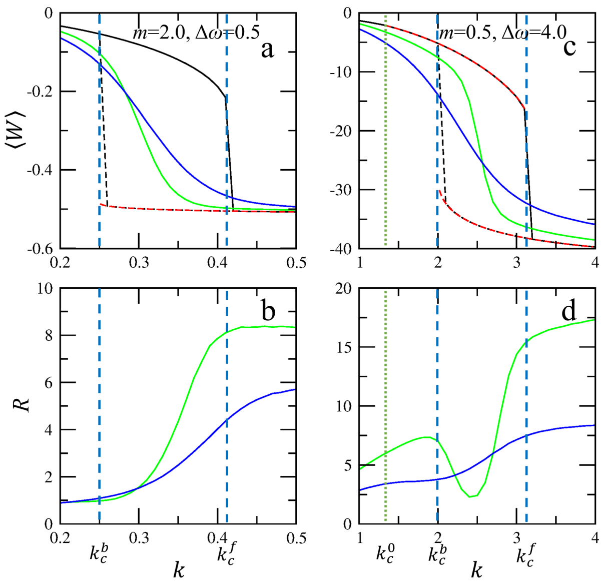

Figure 2: (**a**) Time average work $\langle W\rangle$, Eq. (3), and (**b**) reliability R, Eq. (4), as a function of coupling constant k with $k_BT_1 = k_BT_2 = 10^{-4}$ (black), 0.5 (green), and 1.0 (blue) when $m = 2.0$ and $\Delta\omega = 0.5$. Panels **c** and **d** correspond to $\langle W\rangle$ and R for $k_BT_1 = k_BT_2 = 10^{-4}$ (black solid line), 1.0 (green), and 4.0 (blue) when $m = 0.5$ and $\Delta\omega = 4.0$.

We then develop a stochastic thermodynamics framework to identify physically meaningful heat and work. This is done in a frame in which each oscillator is rotating such that the inertial-like Stuart-Landau dimer can be mapped to two charged particles in a magnetic field [1]. In this frame a single oscillator follows the equations with the two-dimensional double well potential described by $U(|Z|^2) = |Z|^4/4 - (R + m\omega^2)|Z|^2/2$, where $Z = e^{-i\omega t}z$. In this rotating frame, a single oscillator is actually in equilibrium but appears to be in nonequilibrium in the original frame of reference exhibiting limit cycle behavior. Such an equilibrium description sets a reference and hence is key to formulate stochastic thermodynamics. Finally, the work rate can then be computed by applying this driven dynamics to the reference potential, in order to estimate the rate of energy change, and extracting the term which is not heat, which by construction is the term proportional to k. Hence, we get

$$W = -k[(x_1 - x_2)(\dot{x}_1 - \dot{x}_2) + (y_1 - y_2)(\dot{y}_1 - \dot{y}_2) + \Delta\omega(x_1y_2 - y_1x_2)]. \quad (3)$$

At extremely low temperatures (black lines) in Fig. 2 the simulation time is not long enough for the system to relax to its asymptotic state. Hence, in this case the system remains in a metastable state for extremely long times that mimics the noiseless system perfectly. In the metastable regime, the average work shows bistability with the forward (solid black lines) and backward (dashed black lines) initial condition results being distinctly different between the critical backward k_c^b and critical forward k_c^f couplings.

At moderate and high temperatures, we reach the asymptotic state and in this case the bistability disappears, i.e., the solid and dashed (blue and green) lines in Fig. 2 perfectly overlap. The magnitude of work output for the in-phase synchronized regime ($k > k_c^f$) is always larger than the incoherently or the out-of-phase coherently synchronized oscillators. Moreover, even the reliability,

$$R = \left| \frac{\langle W\rangle}{\sqrt{\langle W^2\rangle - \langle W\rangle^2}} \right| \quad (4)$$

that measures how much the average dominates over the fluctuations, is the highest when the oscillators of the working substance synchronize in phase. As a result, overall an in-phase synchronizing working substance always leads to a powerful and reliable machine.

In summary, we studied the stochastic inertial-like Stuart-Landau dimer and extensively analysed our model in the zero temperature limit to uncover the rich phase space structure, which is not observed in the non-inertial system. We then developed a physically meaningful stochastic thermodynamics framework that required a frame transformation due to which the Stuart-Landau oscillator transformed to a magnetic charged particle in a quartic potential. Depending on the physical interpretation of the interaction between the two magnetic charged particles, stochastic heat and work were identified. Our work highlights the importance of a synchronizing working substance in the performance of a machine.

[1] J.-W. Ryu, J.-W. Ryu, A. Lazarescu, R. Marathe, and J. Thingna, New J. Phys. **23**, 105005 (2021).

2.14 Monitoring Quantum Otto Engines

J. Son, P. Talkner, J. Thingna

One of the most distinctive features of quantum physics is the back-action a system receives after a measurement. The simplest one would be the complete decoherence of the system density matrix resulting from a projective measurement. In the context of quantum devices, where coherence might play a major role, such back-actions can induce profound differences. It is critical to assess the ramifications of monitoring schemes applied to quantum thermal machines, since the central thermodynamic quantities, work and heat, are defined by the energy measurements. In this work, we explicitly incorporate two different diagnostic strategies to the many cycle operations of a quantum Otto cycle and compare the performances of these engines.

Two diagnostic protocols analyzed in this work are repeated measurements (RM) and repeated contacts (RC), see Fig. 1. RM is the repetition of standard two-point measurement. For each measurement, a Gaussian pointer interacts with the system and becomes correlated depending on the measurement outcome. Without any additional interaction between them, the energy information is extracted from the pointer, evolving the initial thermal state ρ_0 into

$$\rho_{4N} = \Phi_{4N} \circ \mathcal{V}_{4N} \circ \cdots \circ \Phi_1 \circ \mathcal{V}_1(\rho_0) \qquad (1)$$

with system-pointer interaction

$$\mathcal{V}_i(\rho) = \mathrm{Tr}_\sigma \left[V_i(\rho \otimes \sigma) V_i^\dagger |x_i\rangle_\sigma \langle x_i| \right], \qquad (2)$$

and four-strokes of Otto cycle Φ_{4k+1}, Φ_{4k+3} ($\forall k$) representing work strokes (U and $\tilde{U}$ in Fig. 1), and heat strokes Φ_{4k+2}, Φ_{4k+4} (Φ_h, Φ_c in the same figure). Work strokes are unitary evolution following a time-dependent engine Hamiltonian $H_i = H_c$ for $i = 4k+1, 4k+4$ and $H_i = H_h$ for $i = 4k+2, 4k+3$. Whereas, heat strokes come from the thermalization due to the heat baths of inverse temperatures β_h and β_c. The interaction occurs at time t_i, $i = 1.\cdots, 4N$ through $V_i = e^{-i\kappa(-1)^i H_i \otimes P_\sigma}$ shifting the pointer state by the amount of H_i, which is nothing but the measurement outcome. The pointers are initialized as Gaussian with width Σ and distribution,

$$\sigma = \int dxdy \frac{1}{\sqrt{2\pi\Sigma^2}} \exp\left[-\frac{x^2+y^2}{4\Sigma^2} \right] |x\rangle_\sigma \langle y|. \quad (3)$$

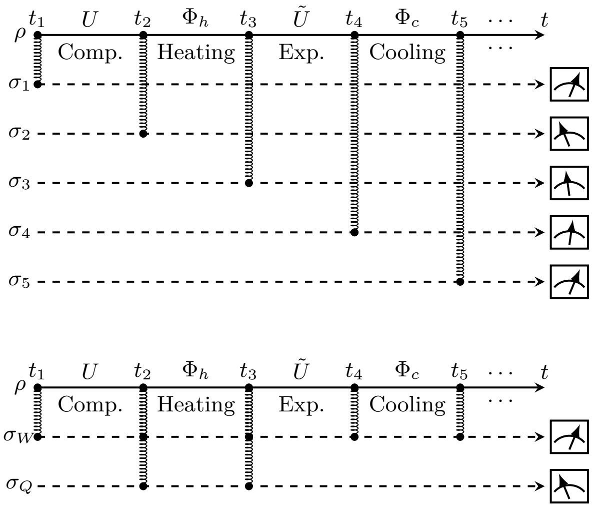

Figure 1: Illustration of RM (above) and two-pointer RC (below) measurement schemes. For N cycles ($4N$ strokes), $4N$ pointers (and thus $4N$ measurements) are applied in RM to record each energy measurement outcome while in RC only the (alternating) sums of energies corresponding to work and heat are measured in two separate pointers. In between the measurements (contacts), the working fluid evolves according to the Otto cycle: compression, heating, expansion, and cooling.

In RC, first introduced in Ref. [2], a pointer contacts with the system many times before the final measurement at the end, giving

$$\begin{aligned} \rho_{4N} &= \mathrm{Tr}_\sigma[\Phi_{4N} \otimes I \circ \mathcal{U}_{4N} \circ \cdots \\ &\circ \ \Phi_1 \otimes I \circ \mathcal{U}_1(\rho_0 \otimes \sigma)|x\rangle_\sigma\langle x|] \quad (4) \\ \mathcal{U}_i(\rho \otimes \sigma) &= V_i(\rho \otimes \sigma) V_i^\dagger, \quad (5) \end{aligned}$$

when only one pointer is attached. In consequence, σ is translated by the outcomes of $(-1)^i H_i$ repeatedly, marking an accumulated sum. It is impossible to separate the contribution from each contact due to the absence of intermediate pointer measurement.

Work is defined as the engine energy change during the work stroke. Total work is then written as $W = \sum_{k=1}^{4N}(-1)^k e_k$ when e_k is the energy after kth measurement (contact). The one corresponding to the heat can be determined similarly. The resulting work probability distribution functions (PDFs) for RM and two-pointer RC are given by the weighted sum of Gaussian peaks centered around different work values with weights multiplied by exponential suppression factors. The two distributions are identical except for the exponential factors and widths of each peak. Exponential factors in RM suppresses any coherence during N cycles, which can be expected from usual von Neumann measurements. For RC, such back-actions become significantly weaker, retaining a large portion of contributions from coherences. Moreover, RC peaks remain sharp with width Σ^2 regardless of the cycle number N, whereas the RM peaks widen as $\sqrt{4N}\Sigma^2$ contributing to the higher fluctuation in the work.

As a concrete example, we modelled two-level system working fluid with Hamiltonians $H_u = \epsilon_u(|+_u\rangle\langle +_u| - |-_u\rangle\langle -_u|)$ with $u = c, h$, driven linearly as $H(t) = -vt\sigma_z/2 - \epsilon_c\sigma_x$ in the first work stroke for finite time $T_1/2$ and following the reverse protocol for the second work stroke. The unitary evolution is set to be non-adiabatic so as to generate coherence during each stroke. Likewise, two cases of thermalization giving a coherent final state are considered, namely perfect thermalization with strong system-bath coupling and imperfect thermalization with weak coupling. In the former case, RC and RM perform similarly: the average values of work are the same and the variance of work differ only by $\mathcal{O}(\Sigma^2)$. On the other hand, in the latter imperfect thermalization model, both average and variance of work develop nontrivial differences. We derived the explicit expression for those quantities analytically for $N = 1$. For N cycles, we examined total work output, efficiency (average work/average heat), reliability (average work/variance of work), and power (average work/total time) numerically. We also optimized power with respect to the work stroke and heat stroke duration to obtain P^* as seen in Fig. 2.

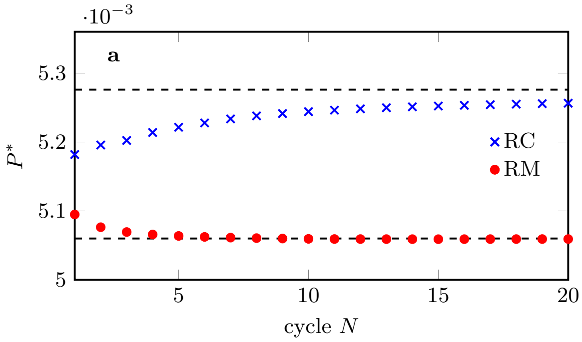

Figure 2: Maximum power P^* with respect to the work stroke and heat stroke duration as a function of the cycle N for RC (blue) and RM (red). Both values converge to their respective asymptotes as $N \to \infty$, plotted as black dashed lines. Parameters used are $\epsilon_c = 1$, $\epsilon_h = 3.7$, $\beta_c = 0.25$, $\beta_h = 0.025$, and $\gamma = 0.025$.

For all N, the work and power of the engine differ by the oscillating function of work stroke time. Efficiency exhibits similar qualitative behaviors, although the differences between the two models are very small. However, reliability and maximum power P^* (Fig. 2) are always substantially higher in the RC monitored engines. Another notable point is the faster convergence when employing RM that occurs since the coherence are destroyed between strokes in RM.

In sum, we verified a weaker back-action of RC and an ability to preserve coherence. These properties alter the average and variances of work and heat when applied to quantum Otto heat engine. Furthermore, from the simple model system, significant improvement in certain figures of merits, e.g. maximum power and reliability, are confirmed. These results establish the necessity of considering measurement effects on the device operations and the potential of tailoring monitoring strategy to the different figures of merit one desires to achieve.

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2.15 Quantum Charging Advantage Cannot Be Extensive Without Global Operations

Ju-Yeon Gyhm, Dominik Šafránek, Dario Rosa

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 we have quantum metrology, which led to the detection of gravitational waves, quantum cryptography, which finds applications in communicating sensitive data, quantum computing, which promises to revolutionize chemistry as well as to speed up or solve important problems in optimization, cybersecurity, data analysis and nanoscale thermodynamic devices, which offer unprecedented precision in thermometry. At large, society is moving towards 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.

Outstanding successes of quantum technologies prompt a question whether quantum effects can also improve the energy storage to satisfy current and future demands. This leads to the notion of quantum battery, which is a quantum mechanical system acting as an energy storage, and in which quantum effects are expected to provide significant advantages over its classical counterpart. Starting from the work of Alicki and Fannes [1], the possibility of using quantum effects (like coherence and entanglement) to increase the performance of a quantum battery has been heavily studied. These studies address several figures of merit, like work extraction, energy storage, charging stability, available energy and charging power, the last being the actual focus of our paper [2].

It has been shown [3] that quantum effects lead to a speedup in the charging power of a quantum battery. The source of this quantum speedup lies in the use of entangling operations, in which the cells are charged collectively as a whole. Those operations, where the number of cells that are being entangled together collectively scales with the system size (i.e., creating multi-partite entanglement), are called *global operations*. In contrast, classical batteries are charged in parallel, meaning that each cell is charged independently of each other. The advantage of this collective versus parallel charging is measured by the ratio Γ, called the *quantum charging advantage* [3]. However, it is still not known *how large* the quantum advantage is in general. To this end, the best known result was [3]

$$\Gamma < \gamma\big(k^2(m-1)+k\big),$$

in which γ is a model-dependent constant, k is the maximum number of cells that are collectively charged, while m (called *participation number*) is the maximum number of parallel charging operations in which a single cell appears.

In principle, this bound allows for a super-extensive scaling of the quantum advantage, meaning that the advantage can scale more than linearly with the number L of cells. For example, consider a charging protocol that has a finite and fixed value of k but having *all-to-all* couplings. In such a case, the participation number of a given cell is of order $m = \binom{L-1}{k-1} \approx (L-1)^{k-1}/(k-1)!$, leading to a quantum advantage of order L^{k-1}.

This prompted a race towards finding the best possible scaling — the authors of [3] found that the scaling is of order L at most through an extensive numerical search. Based on this numerical evidence, they proposed a conjecture that this extensive scaling cannot be surpassed, thus suggesting, but not proving, that the role of the participation number could be rather marginal in determining the best possible scaling. The search for scaling advantages continued in the subsequent years, and all the studies found at most extensive scaling, but it was later shown that some of these advantages were not caused by genuine quantum effects. A genuine, extensive, quantum advantage was found in [4], in a setup including *both* global charging operations and all-to-all couplings. Therefore, the conjecture still held, but remained unproven, together with the unclear role that all-to-all interactions play in determining the quantum advantage.

In our paper [2], we prove this conjecture, showing that a quantum battery provides *at most* extensive advantage over classical batteries. Furthermore, we show that this scaling is achievable only via *global* charging operations, *i.e.*, we show that all-to-all interactions, and more generally, the participation number, does not provide any scaling advantage.

We first provide a *general* theorem, bounding the maximum charging power achievable with a *general* quantum battery with any general Hamiltonian, not necessarily realized by L identical cells, thus including also more general cases described in the literature. The main idea of the theorem is to show that the charging power is *entirely* determined by the maximum energy amount that a *single* parallel operation can deposit into the battery, while the number of parallel operations, *i.e.* the participation number, does not provide any further contribution to the charging power. The conjecture is then proven as a consequence of this main theorem, once it is applied to the battery made of identical cells. Together with examples showing extensive advantage [4], already found and discussed in the literature, this result concludes the quest for the best possible scaling which can be obtained by quantum batteries.

Our result not only show that the maximum possible scaling with the number of cells of the quantum advantage is linear. We have also pinpointed the exact source of this advantage while ruling out any other possibilities, providing an explicit way of designing such batteries so this advantage can be achieved. Consequences are far-reaching. For example, electric vehicles use around $200-7000$ cells in a car battery, and the typical charging time is about 10 hours. Employing quantum charging and making use of the best possible quantum advantage could cut the charging time by $200-7000$ times. This in turns would imply reducing the charging times from 10 hours to less than 3 minutes.

Employing these technologies might push electric vehicles beyond the tipping point, making them fully competitive on the market.

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2.16 Operator delocalization in quantum networks

Joonho Kim, Jeff Murugan, Jan Olle, Dario Rosa

The conjecture that black holes are the fastest scramblers of information in nature has precipitated a renewed interest into questions of thermalization and ergodicity in quantum systems, and ushered in a new era of collaboration between seemingly disparate fields like high energy theory, condensed matter physics and quantum information. In this regard, one particularly important development in the past five years has been the emergence of the Sachdev-Ye-Kitaev (SYK) model

$$\hat{H}^{(q)}_{\mathrm{SYK}} = \mathrm{i}^{q/2} \sum_{i_1<\cdots<i_q} J_{i_1\cdots i_q} \hat{\gamma}^{i_1} \cdots \hat{\gamma}^{i_q} \,, \qquad (1)$$

of disordered Majorana fermions as a canonical framework to study questions from the information-loss paradox in (low-dimensional) quantum gravity to the physics of spin-glasses. The SYK model in turn has led to the development of a host of new (or, sometimes, forgotten) tools such as out of time-order correlators (OTOCs), spectral analysis of operators and computational complexity to attack quantum many-body problems. Indeed, our paper [1] arose from our trying to answer the question: *What is it that makes the SYK model so special?* Is it the Majorana fermions? Or its quenched random couplings? Perhaps, it is the all-to-all q-fermi interactions?

An obvious starting point to answer this question would be to focus on the scrambling properties of the SYK model. Associated with the fact that the SYK$_q$ model (for $q \geq 4$) saturates the Maldacena-Shenker-Stanford (MSS) bound [2] on the leading Lyapunov exponent $\lambda_{\mathrm{L}} \leq 2\pi T$, it was recently argued that scrambling is better understood in terms of the growth of the size of time-evolving operators in the model. The idea is that in a scrambling system, the probability distribution of the size of the operator, $P_s(t)$, shifts towards larger operators with an initial exponential rate determined by the infinite-temperature chaos exponent.

We start instead from the seemingly very simple observation that scrambling in a many-body system is actually made up of two distinct processes: an initial small operator first grows to a sufficiently large size; at the same time, the grown operator delocalizes over the Hilbert space of large operators. Our main goal in [1] has been to study the latter phase only, which we call *operator delocalization*, in as simple (and universal) a setup as possible, to understand how it can be controlled, with the ultimate goal of improving our understanding of scrambling and quantum chaos.

To elaborate, we study the SYK$_2$ model. Even though this model is essentially free, the quenched random couplings J_{ij} and Majorana fermions $\hat{\gamma}^i$ endow the system with a rich structure that has garnered much recent attention. We go even further and define the model on a random graph $G(V, E)$, consisting of a collection of vertices V and edges $E \subseteq V \otimes V$ with the connectivity of the graph encoded into matrix of couplings, J_{ij}, now interpreted as the adjacency matrix of the graph.

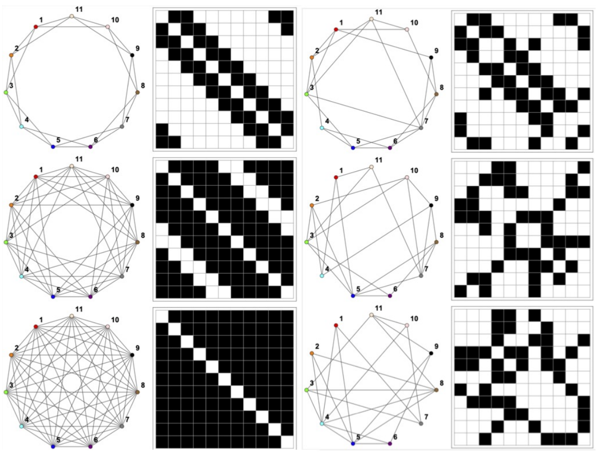

Figure 1: Examples of Random graphs used in the study.

In Fig. 1 we report examples of random graphs of interest and their corresponding adjacency matrices.

The key observation is that, since the SYK$_2$ model is free, we do not expect any operator growth through Hamiltonian evolution [3] but this does not mean that the system is trivial.

We show that operator hopping induces non-trivial dynamics of the system which is *heavily* controlled by the underlying graph. Our results show that operator delocalization requires two ingredients, *i.e.* (i) sufficiently non-local operators (either obtained by the growing dynamics of initially small operators or directly as initially large operators) and (ii) networks that are able to utilise the non-locality. At the technical level, we measure the delocalization properties by means of the notion of *K-complexity*, C_K, introduced in [4]. It describes the delocalization of an operator in a finite dimensional Hilbert space with respect to a specific basis - the Krylov basis.

We can then compute the time evolution of C_K for both large size and small size operators, both for graphs with small randomness and large randomness. The results are reported in Fig. 2.

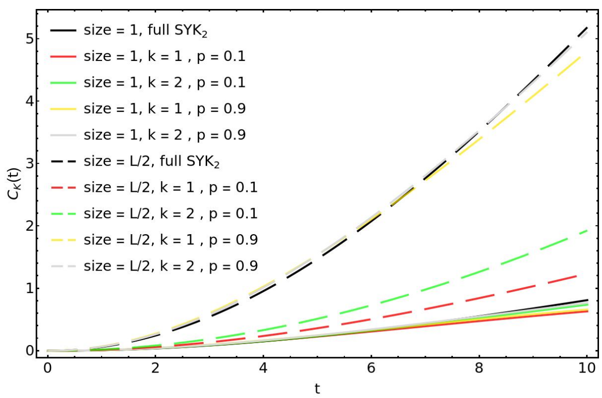

Figure 2: The early time behavior of K-complexity for graphs with small randomness $p = 0.1$ and graphs with large randomness $p = 0.9$. Full (dashed) lines denote small (large) size operators.

We clearly see that, when dealing with small size operators, the evolution of $C_K(t)$ is almost independent on the randomness of the graph: this is just in agreement with the non scrambling properties of the SYK$_2$ model. However, when the model is provided with large size operators, we see that the behavior of $C_K(t)$ is *highly* dependent on the randomness of the underline graph. This result show that even in absence of operator growth, the dynamics can be made non-trivial, at the cost of considering from the very beginning operators of large sizes. This marked distinction can be made more explicit by considering, instead of the quantity $C_K(t)$, another time-independent quantity, denoted by $R(L)$, which measure for a given system size L the delocalization properties of large size operators compared to that of small size operators. The behavior of $R(L)$ is reported in Fig. 3 from which we can clearly see a completely different scaling.

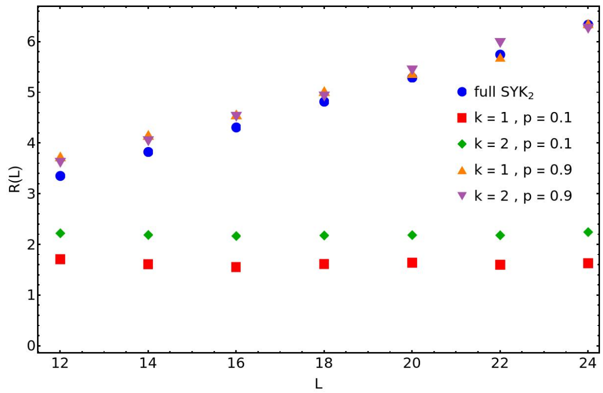

Figure 3: The behavior of $R(L)$ as a function of the system size for small randomness graphs ($p = 0.1$) as well as large randomness graphs ($p = 0.9$).

All in all, our results show that operator delocalization can be non-trivial even in absence of genuine operator growth and scrambling dynamics and that this physical phenomenon is highly controlled by the geometrical properties of the connections in the system. As a next step, it will be crucial to understand how much the operator delocalization properties of a given, non-scrambling, Hamiltonian control the scrambling dynamics upon inserting a small scrambling perturbation in the setup.

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2.17 Higher-Order Topological Corner State Tunneling in Twisted Bilayer Graphene

Moon Jip Park, Sunam Jeon, SungBin Lee, Hee Chul Park, Youngkuk Kim

We study the novel quantum tunneling effect between the corner states in twisted bilayer graphene(TBG). The tunneling problem is described by the instantons, which represent the semiclassical paths of the tunneling. The tunneling between the topological corner states are comprised of the instantons that circulate the closed edge of the two-dimensional bulk of the TBG. An instanton path and its complementary anti-instanton path as a pair form a full circle of the edge[See Fig. 1 (a)]. Our main discovery is the quantum interference effect between the instanton paths, arising from the intrinsic Berry phase as the electron adiabatically circulates the higher-order topological insulator(HOTI) bulk. This topological interference effect manifests as the oscillatory behavior of the intercorner tunneling and the energy splitting of the corner states. We demonstrate that the instanton tunneling oscillation is measurable through resonant transport. As a result, our work offers a promising platform for the hunt for the two-dimensional HOTI.

We start our discussion by presenting a simple model capturing the higher-order topology of TBG. The atomic configuration of the TBG is constructed by twisting AA-stacked bilayer graphene with respect to the collinear axis at the hexagonal center. At arbitrary angles, the short-ranged interlayer coupling can open a bandgap in the TBG. In such case, the TBG in the presence of the global band gap becomes the two-dimensional HOTI possessing the corner states, regardless of the twist angle [See Fig. 1 (a)]. The physical origin of the corner states can be intuitively understood using the equivalent C_{2x} winding number with the additional C_{2x} symmetry. The C_{2x} winding number is defined as the Berry phase of each C_{2x} sector along the C_{2x} invariant line in the Brillouine zone. The physical manifestation of the non-trivial winding number is the topological crystalline insulator phase possessing the 1D helical edge modes at C_{2x} preserving boundaries. However, an arbitrary boundary termination may not preserve C_{2x} symmetry. As such, the edge states are gapped except for the corners preserving C_{2x}, leaving the zero-dimensional topological corner states.

This situation can be also mathematically formulated using the Jackiw-Rebbi soliton formulation of the HOTI in the disk geometry. The formulation considers the edge modes in the disk geometry of the radius, R, with the angle dependent hybridization gap:

$$H = \Psi^\dagger(\theta)[i\frac{v_F}{R}\partial_\theta \tau^z + \Delta \sin\theta(e^{i\theta}\tau^+ + e^{-i\theta}\tau^-)]\Psi(\theta), \quad (1)$$

where $\Psi(\theta) = (\psi_1(\theta), \psi_2(\theta))^T$ is the spinor of counter propagating edge mode with the Fermi velocity v_F. $\tau^z = \pm 1$ represents the chirality of the edge modes. $\Delta \sin\theta$ represents the angle dependent hybridization. The strength of the hybridization vanishes at C_{2x} symmetric corners($\theta = 0, \pi$) that host an effective domain wall of the well-known Su-Schrieffer-Heeger(SSH) chain. The physical consequence is the emergence of the localized corner modes at $\theta = 0$ and $\theta = \pi$.

Physically, two independent tunneling paths connect the corner states[See Fig. 1 (c)]. One is the clockwise circulation($\theta \to \theta + \pi$), and the other is the counter-clockwise circulation($\theta \to \theta - \pi$). The total tunneling amplitude between the corner states at $\theta = 0$ and π is given as the sum of the instantons, possessing $n_{I(A)}$ number of the clockwise(counter-clockwise) circulations as,

$$S_{\rm tot} = \sum_{n_I, n_A \geq 0}^{n_{\rm I}+n_{\rm A} \text{odd}} S(n_{\rm I}, n_{\rm A}) \quad (2)$$

where $S(n_{\rm I}, n_{\rm A})$ is the amplitude of the tunneling (For microscopic derivation, see supplementary materials). The C_{2x} symmetry, when it is preserved, relates the clockwise and the counter clockwise paths, and thus the instanton representing these paths do not acquire phase

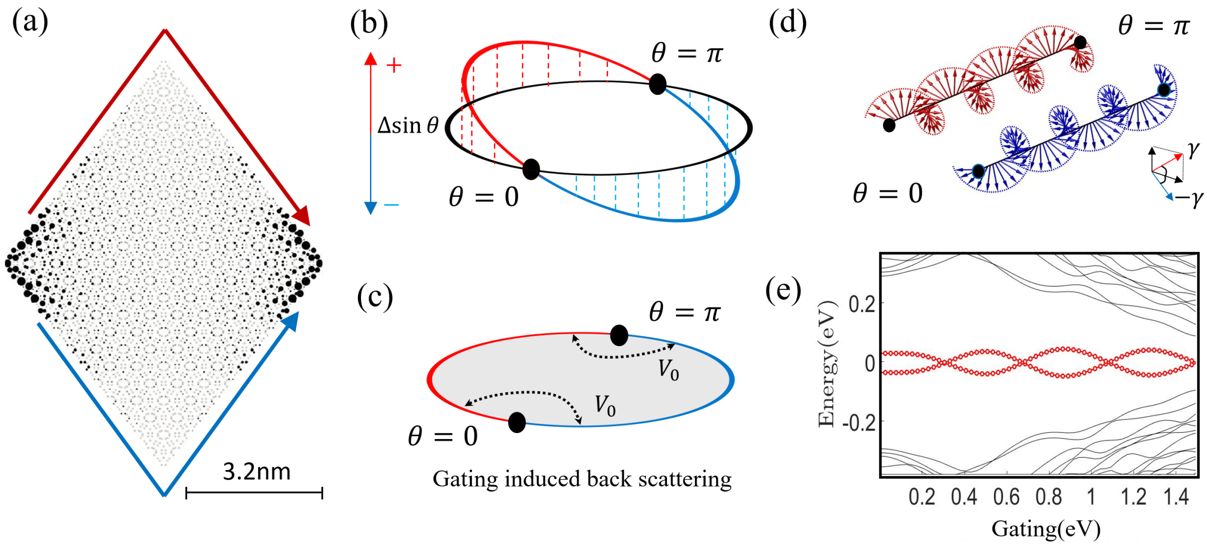

Figure 1: (a) Transport setup of TBG, which consists of two misaligned graphene nanoribbons. The overlapping region of two nanoribbons forms the HOTI phase while the non-overlapping regions serve as the metallic contacts. The instanton tunneling between the corner states mediates the electronic transmission from contact 1 to contact 2. Inset: example of the gate structure. The TBG is encapsulated by the dielectric hBN. (b) Normalized transmission of electrons from contact 1 to contact 2 as a function of the gate voltage with various values of the broadening. The non-zero transmission occurs through the instanton tunneling between the topological corner states. The instanton interference effect causes the oscillatory behaviors in the transmission peak. At the nodes of the oscillations, the transmission peaks vanish as they destructive interfere. (c) Schematic illustration of the Landauer-Büttiker transport. Electron tunneling from contact 1 to contact 2 occur through the resonant tunneling of the corner states(Red line), separated by the instanton gap, ΔE. (d) Normalized tunneling current derived by integrating the transmission in (b). The perfect suppression of the tunneling current occur at the nodes of the instanton oscillations(red lines). (e) The evolution of corner states energies as a function of the gate voltage. The energy splitting oscillates as a function of the gate voltage with the frequency ΔV.

difference. However, if the external gate voltage applied along $\hat{z}-$direction, the top and the bottom layers energetically splits. As a result, C_{2x} symmetry, which exchange the top and the bottom layer is explicitly broken. Once C_{2x} symmetry is broken, the finite phase difference between the two instantons can enter, and it leads to the interference effect.

The overall effect of the gate voltage is now to separate the clockwise and the counter clockwise instanton contributions by the opposite geometric phases, $\pm\gamma$, respectively, as the electron travel from one corner to the other. The direct physical manifestation of this novel interference effect is the oscillatory behavior of the energy splitting between the corner states[See Fig. 1 (e)]. The energy splitting oscillates as a function of the geometric phase difference γ, and it vanishes whenever the destructive interferences occur($\gamma = (N + \frac{1}{2})\pi$, where $N \in \mathbb{Z}$). This feature establishes the gate-tunable instanton interference effect, which is the main finding of our paper. It is important to note that this result is based on the global gauge structure arising from the intrinsic Berry phase, and do not depend on the details of the wave functions. In other words, the gate voltage acts as the effective flux, similar to that of the Aharonov-Bohm effect. Yet, an important difference with the Aharonov-Bohm effect is that the gate voltage acts as a pseudo-flux that preserves the time-reversal symmetry.

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2.18 Disorder-driven Phase Transitions of Second-order Non-Hermitian Skin Effects

Kyoung-Min Kim, Moon Jip Park

In this work, we study the disorder-driven phase transition of the second-order non-Hermitian skin effect(NHSE). Although the disorder-induced topological phase transition has been extensively studied in the Hermitian topological systems, we show that the extensiveness of the boundary modes plays a crucial role, and we newly discover the dynamical phase transition of the NHSE. At the phase transition, we observe a novel mobility edge phenomena, which the bulk energy spectrum is separated into the trivial bulk modes and the NHSE bulk modes characterized by second-order NHSE Hamiltonian. The physical manifestation of this dynamical phase transition is the NHSE corner modes, which form an arc in the complex energy plane. As a result, we find that a single band spectrum shows the coexistence of the NHSE bulk modes and the trivial bulk modes. Our work reveals rich physical behaviors of the disordered NHSE in non-Hermitian systems.

To construct the model of the second-order NHSE, we consider the following dual relation of the non-Hermitian Hamiltonian, $H_{\mathrm{NH}}(\mathbf{k})$ and the extended Hermitian Hamiltonian $H_{\mathrm{BBH}}(\mathbf{k})$ as,

$$H_{\mathrm{BBH}}(\mathbf{k}) = \begin{pmatrix} 0 & H_{\mathrm{NH}}(\mathbf{k}) \\ H^{\dagger}_{\mathrm{NH}}(\mathbf{k}) & 0 \end{pmatrix}, \quad (1)$$

where $H_{\mathrm{BBH}}(\mathbf{k})$ is the Bloch Hamiltonian of the Benacazar-Bernevig-Hughes(BBH) model, which shows the Hermitian higher-order topological insulator phase. The non-Hermitian dual Hamiltonian, $H_{\mathrm{NH}}(\mathbf{k})$, is explicitly given as, $H_{\mathrm{NH}}(\mathbf{k}) = -i(\gamma + \lambda \cos k_x) + (\gamma + \lambda \cos k_y)\sigma_y + \lambda(\sin k_x \sigma_z + \sin k_y \sigma_x)$, where σ_i is i-th Pauli matrices. In real space, this model forms the Su-Schrieffer-Heeger(SSH) like dimerized chain along k_y direction and the Hatano-Nelson like asymmetric hopping terms along k_x direction (See Fig. 1 (a)-(c)). The bulk energy spectrum exhibits the line gap along the imaginary axis in the complex energy plane ($\mathrm{Re}z = 0$). The line gap closes when $|\gamma/\lambda| = 1$ accompanying the topological phase transition of the second-order NHSE. The second-order NHSE occurs when $|\gamma/\lambda| < 1$, and the physical manifestation is the emergence of the localized corner modes in the open boundary condition (Red lines in Fig. 1 (e)). In contrast to the Hermitian second-order topological insulator, the number of the corner modes grows in order of $O(L)$, where L is the system length.

We introduce the additional auxiliary parameter $t \in [0,1]$, and consider the adiabatic deformation of the non-Hermitian Hamiltonian into the trivial atomic insulator as, $H(\mathbf{k}, t=0) = H_{\mathrm{NH}}(\mathbf{k})$ and $H(\mathbf{k}, t=1) = \sigma_x$. During the adiabatic deformation, the non-Hermitian Hamiltonian can be singular-value decomposed as, $H(\mathbf{k}, t) = U^{\dagger}_{\mathbf{k}} D_{\mathbf{k}} V_{\mathbf{k}}$, which allows to define a unitary matrix, $q_{\mathbf{k}} \equiv U^{\dagger}_{\mathbf{k}} V_{\mathbf{k}} = \sum_n e^{i\lambda_n(\mathbf{k})} |n(\mathbf{k})\rangle\langle n(\mathbf{k})|$, and the corresponding phase $\lambda_n(\mathbf{k})$. Using the unitary matrix, $q_{\mathbf{k}}$, we can define $\mathbb{Z}_2$-valued three-dimensional winding number of $\lambda_n(\mathbf{k})$ as,

$$\mathcal{W} = \frac{1}{24\pi^2} \int_0^1 dt \int d^2\mathbf{k} \epsilon^{ijk} \mathrm{Tr}[q^{\dagger}_{\mathbf{k}} \partial_i q_{\mathbf{k}} q^{\dagger}_{\mathbf{k}} \partial_j q_{\mathbf{k}} q^{\dagger}_{\mathbf{k}} \partial_k q_{\mathbf{k}}]. \quad (2)$$

It is shown that C_4-rotational symmetry quantizes the winding number as it takes non-trivial (trivial) value, $\mathcal{W} = 1/2(0)$ if $|\gamma/\lambda| < 1(|\gamma/\lambda| > 1)$.

After establishing the second-order NHSE in the clean limit, we now consider the addition of the on-site random disorder in the Hamiltonian. Motivated by the C_4-rotational symmetry we first analyze the particular type of the onsite disorder, $V_{\mathrm{dis}} = \sum_i \omega_i (I_2 - i\sigma_y) c^{\dagger}_i c_i$. Here c_i is the annihilation operator in i-th site, and w_i is the uniformly distributed random number within the window of $w_i \in [-W/2, W/2]$. The introduction of the random disorder term immediately breaks the translational symme-

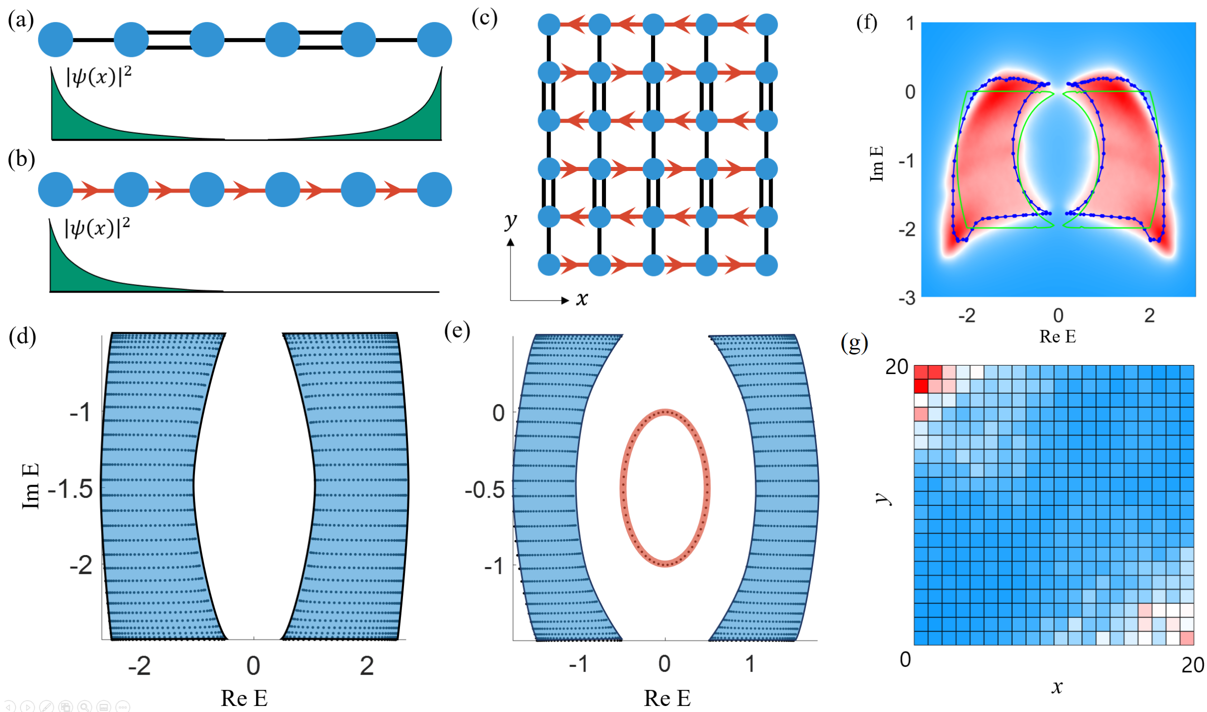

Figure 1: (a)-(c) Schematic illustration of (a) the one-dimensional SSH chain, (b) Hatano-Nelson model, and (c) the higher-order NHSE. While the SSH chain with the dimerized hoppings hosts the pair of the localized boundary modes, the Hatano-Nelson model with the asymmetric hopping (colored by the red arrow) exhibits the collapse of bulk modes into the localized modes at only one end. The model of the Higher-order NHSE is constructed by the asymmetric non-Hermitian hopping term in $\hat{x}-$direction and the dimerized hopping in $\hat{y}$-direction. The physical manifestation of the higher-order NHSE is $O(L)$ numbers of the corner modes. (d)-(e) The typical band structure of the second-order NHSE in (d) trivial and (e) non-trivial regime. The blue surface and red line represents the bulk modes and the NHSE corner modes respectively.(f) The DOS in the complex energy plane. The surface plot indicates the DOS in the presence of the disorder obtained by the brute-force numerical diagonalization. The green solid line is the band structure in the clean limit. The blue dotted line indicates the deformed band structure. (g) typical wave function profile of the disorder-induced corner modes in real space.

try of the systems. However, the effective Bloch Hamiltonian can be derived by averaging many disorder configurations until it restores the translational symmetry. Fig. 1 (f)-(g) shows the density of states at the critical point of the topological phase transition, $(\gamma/\lambda = 1)$ in the presence of the disorder $(W = 2)$. We observe a clear deviation of the disordered density of states, compared to the band structure in the clean limit (red surface and green solid lines in Fig. 1 (f)). The deformation of the effective band structure has strong energy dependence in the complex energy plane. For example, in the upper half part of the band structure, the bandwidth along the real axis suppresses, while the lower half part shows the extension of the bandwidth. This contrasting tendency in the deformation of the band structure indicates the strong energy-dependent renormalization due to the disorder. The overall band deformation can be explained by the renormalization of the topological mass, γ. Furthermore, the renormalization of the topological mass drives the disorder-induced second-order NHSE in the trivial non-Hermitian systems.

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2.19 One-particle spectral functions of the half-filled 1D Hubbard model at zero and finite magnetic fields

J.M.P. Carmelo, T. Čadež, P.D. Sacramento

Using the Bethe ansatz we theoretically study the one-particle spectral functions in the half-filled 1D Hubbard model in both zero and finite magnetic field [1]. The one-particle excitations are gapped and exhibit fractionalization identified as the spin-charge separation. The phenomenon has been previously observed in the tunneling spectroscopy experiments in quantum wires [2], electrostatically gated semiconducting heterostructures [3] as well as in the angle resolved photoemission spectroscopy (ARPES) of $SrCuO_2$ [4] and $MoSe_2$ [5].

The Hubbard model with one fermion per site in a magnetic field h under periodic boundary conditions on a 1D lattice with an even number of sites is given by

$$\hat{H} = \hat{H}_H + 2\mu_B h \hat{S}_s^z \qquad (1)$$

with $\hat{H}_H = t\hat{T} + U\hat{V}_D$ and

$$\hat{T} = -\sum_{\sigma=\uparrow,\downarrow}\sum_{j=1}^{L}(c_{j,\sigma}^\dagger c_{j+1,\sigma} + c_{j+1,\sigma}^\dagger c_{j,\sigma}),$$

$$\hat{V}_D = \sum_{j=1}^{L}\rho_{j,\uparrow}\rho_{j,\downarrow}; \qquad \rho_{j,\sigma} = c_{j,\sigma}^\dagger c_{j,\sigma} - 1/2,$$

are the kinetic-energy operator in units of t and the on-site repulsion operator in units of U, respectively. The operator $c_{j,\sigma}^\dagger$ (and $c_{j,\sigma}$) creates (and annihilates) a $\sigma =\uparrow,\downarrow$ fermion (electron or atom) at lattice site $j = 1, ..., L$. In Eq. (1) μ_B is the Bohr magneton, for simplicity, in $g\mu_B$ we have taken the Landé factor to read $g = 2$, and the operator $\hat{S}_s^z = -1/2\sum_{j=1}^{L}(c_{j,\uparrow}^\dagger c_{j,\uparrow} - c_{j,\downarrow}^\dagger c_{j,\downarrow})$ is the diagonal generator of the model global spin SU(2) symmetry.

Our goal is the study of the line shape of the up- and down-spin one-particle spectral functions at and in the (k, ω) plane's vicinity of such functions's cusp singularities by means of a suitable dynamical theory. The latter refer to peaks in the vicinity of which most one-particle spectral weight is located. Specifically we calculate the Mott-Hubbard gap, the one-particle excitation spectra, the exponents of the power law divergencies along the most important lines in the spectra (called branch lines) and discuss the relation of our results to the condensed-matter and ultracold spin-1/2 atom systems.

The Mott-Hubbard gap is shown in the left panel of Fig. 1 as a function of the dimensionless parameter $u = U/4t$, where U is the onsite Coulomb repulsion and t the nearest neighbour hopping, at fixed spin density $m = 0$ (unpolarized case) and $m = 1$ (fully polarized case) and in the right panel of Fig. 1 as a function of spin density m for $u = 0.4, 1, 5$.

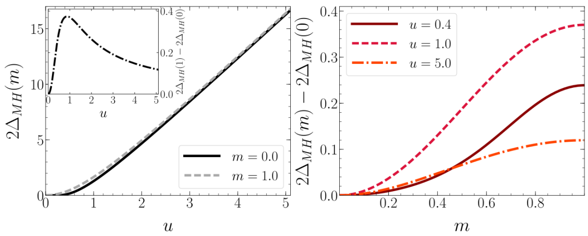

Figure 1: Left panel: the Mott-Hubbard gap $2\Delta_{\mathrm{MH}}$ in units of t as a function of $u = U/4t$ for spin densities $m = 0$ and $m = 1$. The inset shows the difference $2\Delta_{\mathrm{MH}}(1) - 2\Delta_{\mathrm{MH}}(0)$ as a function of u. Right panel: the small deviation $2\Delta_{\mathrm{MH}}(m) - 2\Delta_{\mathrm{MH}}(0)$ in units of t as a function of the spin density m for $u = 0.4, 1.0, 5.0$.

Within the dynamical theory used in our studies, the up-and down-spin spectral functions B_σ, have for $\omega < 0$ and small values of the deviation $(\omega + \epsilon_{\sigma,\beta(k)}) \leq 0$ at and near a $\beta = c, c', s$ branch line $\epsilon_{\sigma,\beta(k)}$ the following general behavior

$$B_\sigma(k,\omega) \propto (\omega + \epsilon_{\sigma,\beta(k)})^{\xi_\beta^\sigma(k)} \qquad (2)$$

where $\xi_\beta^\sigma(k)$ are the momentum-dependent exponents which determine the singular behavior near the corresponding branch line. As an example we show in Fig. 2 the unpolarized (zero magnetic field) case $m = 0$. The full colored lines are the calculated branch lines $\epsilon_{\sigma,\beta(k)}$, where $\beta = s$ (green line) corresponds to the branch line of spin excitations, whereas $\beta = c, c'$ (blue and red lines) correspond to charge excitations. Above the s and c lines (white region) there are no excitations, whereas below (shaded region) there is a continuum of excitations. At the branch lines the singular behaviour of the spectral function occurs as captured by Eq. (2). In our work [1] we also calculate the corresponding momentum-dependent exponents $\xi^{\sigma}_{\beta}(k)$ for each branch line (not shown here), the negative values of which indicate singularities in the spectral function. Similar analysis is performed also for finite spin densities (finite magnetic fields).

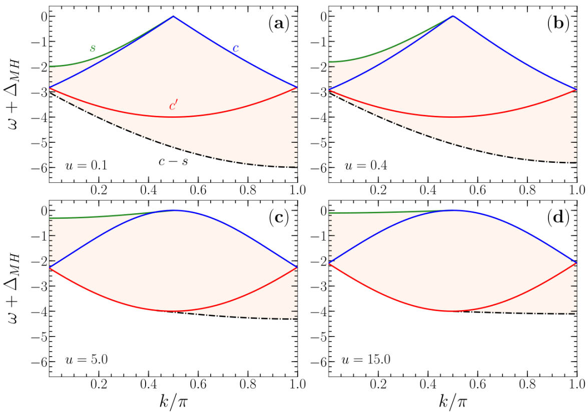

Figure 2: The (k,ω)-plane regions defined by the spectrum $\epsilon_{\sigma}(k)$, where for spin density $m = 0$ and (a) $u = 0.1$, (b) $u = 0.4$, (c) $u = 5.0$, and (d) $u = 15.0$ there is in the thermodynamic limit more spectral weight in the removal one-particle spectral function. Most spectral weight is located in the vicinity of the c, c', and s branch lines and of the c s boundary line represented here by solid lines and a dashed-dotted line, respectively.

The interacting spin-1/2 fermions described by the model under study here can either be electrons or spin-1/2 atoms. In condensed matter materials at zero magnetic field, ARPES directly measures the spectral function of the electrons, which are removed via the photoelectric effect. On the other hand, the 1D Hubbard model with one fermion per site in a magnetic field can be implemented with ultra-cold atoms. Momentum-resolved radio-frequency (rf) spectroscopy and Bragg spectroscopy are techniques to measure the spectral functions in ultracold atomic systems. In particular, momentum-resolved rf is a tool to achieve an analog of ARPES for ultracold atomic systems. The spectroscopy takes advantage of the many spin states of the atoms in these systems.

Can the (k,ω)-plane distribution of spectral peaks at finite magnetic field associated with the cusp singularities of our theoretical predictions be accessed by ultracold spin-1/2 atomic experiments? In a magnetic field, the degeneracy of the atoms's spin states is split by the Zeeman interaction at magnetic field strengths around the Feshbach resonance. This Zeeman splitting is much larger than other energy scales in the system. Fortunately, all the spin-relaxation mechanisms available to atoms in some of their spin states are either forbidden or strongly suppressed, so a system of atoms in those spin states stays that way without relaxing.

Momentum-resolved rf spectroscopy takes advantage of the fact that the rf photon has a negligible momentum compared to the momentum of the atom. As a result, the spin-flip transition does not change its momentum state. In the language of photoemission spectroscopy, this is a vertical transition. The momentum of the spin-flipped atom, and thus the momentum of the atom inside the interacting system, can be measured in a time-of-flight experiment. Importantly, with this information, one can indeed reconstruct the one-particle spectral function and thus use the present results as a theoretical prediction and check their relevance and consequences for actual physical systems.

Hence, our theoretical predictions are of experimental interest for condensed-matter chain compounds at $m = 0$ where they can be tested by ARPES and for systems of ultracold spin-1/2 atoms on optical lattices for finite spin densities.

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2.20 Nanomechanics driven by Andreev tunneling

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

We predict and analyze mechanical instability and corresponding self-sustained mechanical oscillations occurring in a nanoelectromechanical system composed of a metallic carbon nanotube (CNT) suspended between two superconducting leads and coupled to a scanning tunneling microscope (STM) tip [1]. We show that such phenomena are realized in the presence of both the coherent Andreev tunneling between the CNT and superconducting leads, and an incoherent single electron tunneling between the voltage biased STM tip and CNT. Treating the CNT as a single-level quantum dot, we demonstrate that the mechanical instability is controlled by the Josephson phase difference, relative position of the electron energy level, and the direction of the charge flow.

We consider a metallic single-wall carbon nanotube suspended between two grounded SC electrodes and coupled to a scanning tunneling microscope (STM) tip via electron tunneling. The two SC electrodes are characterized by the same modulus Δ and different phases $\phi_{L,R}$ of SC order parameter, and corresponding Josephson phase difference $\phi = \phi_R - \phi_L$. We study the case where the CNT mean-level spacing is greater than temperature k_BT and the bias voltage eV applied between STM tip and CNT. It allows us to treat the CNT as a movable single-level quantum dot (QD). The capacitive coupling between the CNT and a gate is controlled by a gate voltage V_g. We also assume the dynamics of the CNT bending is reduced to the dynamics of the fundamental flexural mode.

The Hamiltonian of the model reads as follows

$$H = H_N + H_S + H_{CNT} + H_{tun}. \tag{1}$$

The first two terms are the Hamiltonians of an STM tip (normal lead) and two SC leads, accordingly:

$$H_N = \sum_{k\sigma}(\varepsilon_k - eV)c^\dagger_{k\sigma}c_{k\sigma}, \tag{2}$$

$$H_S = \sum_{kj\sigma}\left\{\xi_{kj}a^\dagger_{kj\sigma}a_{kj\sigma} - \Delta e^{i\phi_j}(a^\dagger_{kj\uparrow}a^\dagger_{-kj\downarrow} + H.c.)\right\} \tag{3}$$

Here, $c_{k\sigma}$ ($c^\dagger_{k\sigma}$) and $a_{kj\sigma}$ ($a^\dagger_{kj\sigma}$) are annihilation (creation) operators of electrons in the normal and jth SC leads ($j = L, R$) with energies ε_k and ξ_{kj}, correspondingly. The index $\sigma =\uparrow,\downarrow$ indicates the spin of electrons in the leads.

The Hamiltonian of the single-level vibrating CNT-QD reads as follows

$$H_{CNT} = \sum_\sigma \varepsilon_0 d^\dagger_\sigma d_\sigma + \frac{\hbar\omega_0}{2}(\hat{p}^2 + \hat{x}^2) - F\hat{x}\sum_\sigma n_\sigma. \tag{4}$$

The quantum dynamics of the electronic degree of freedom is described by the first term in Eq. (4), where ε_0 is the QD electron energy level, and d_σ, $d^\dagger_\sigma$ are annihilation and creation operators of the electrons in the QD, $n_\sigma = d^\dagger_\sigma d_\sigma$. The second term characterizes the CNT vibrations with the frequency ω_0, and the dimensionless operators $\hat{x} = \hat{X}/x_0$, $\hat{p} = x_0\hat{P}/\hbar$ are canonically conjugated displacement and momentum of the CNT-QD. Here, $x_0 = \sqrt{\hbar/m\omega_0}$ is the amplitude of the zero-point oscillations of the CNT, and m is the mass of the CNT. Electromechanical interaction determined by the third term in Eq. (4) is achieved through the electrostatic interaction of the charged CNT-QD with the gate electrode. The interaction strength is $F \propto (ex_0/h)V_g\beta$, where h is the distance between the CNT and gate electrode, and $\beta \sim 0.1$ is a geometrical factor associated with the capacitances in the system. The last term in Eq. (1),

$$H_{tun} = \sum_{k\sigma} e^{-\hat{x}/\lambda}\left(t^n_k c^\dagger_{k\sigma}d_\sigma + (t^n_k)^* d^\dagger_\sigma c_{k\sigma}\right) + \sum_{kj\sigma}\left(t^s_k a^\dagger_{kj\sigma}d_\sigma + (t^s_k)^* d^\dagger_\sigma a_{kj\sigma}\right), \tag{5}$$

describes the tunneling processes between the CNT and (i) the STM tip with deflection dependent hopping amplitude, i.e., $t^n_k \exp(-\hat{x}/\lambda)$,

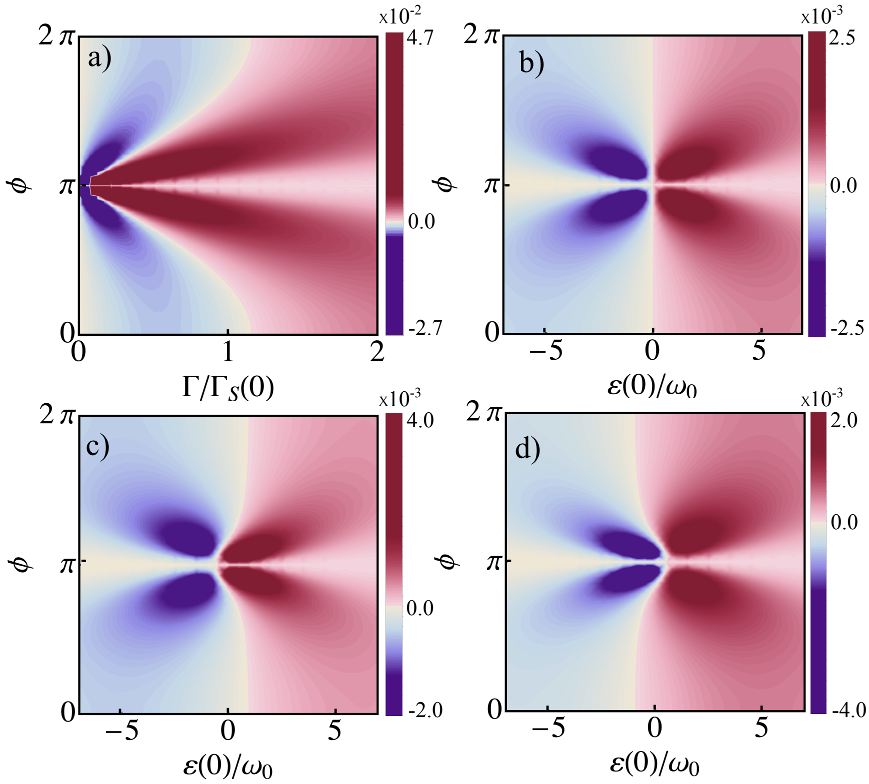

Figure 1: Phase diagrams of the mechanical instability showing pumping coefficient $\eta(0)$ as a function of the Josephson phase difference ϕ, the QD level width $\Gamma/\Gamma_S(0)$, and the QD energy level $\varepsilon(0)/\omega_0$. The red and blue color schemes indicate the mechanical instability ($\eta > 0$) and the damping ($\eta < 0$) regimes, respectively.

where $\lambda = l/x_0$ and l is the tunneling length of the barrier; (ii) SC leads with the hopping amplitude t_k^s.

The various dependencies of the pumping coefficient $\eta(0)$ on the parameters ϕ, $\Gamma/\Gamma_S(0)$, and $\varepsilon(0)$ are shown in Fig. 1. Red color scheme in Fig. 1 indicates the regime of mechanical instability $\eta(0) > 0$, while blue scheme shows the region of the overdamped mechanical oscillations $\eta(0) < 0$. In the case $\varepsilon(0)$=ε_0=0, the pumping coefficient $\eta(0) \propto \kappa\alpha/\lambda$ is determined by the ratio between Γ and $\Gamma_S(\phi)$. The pumping coefficient changes its sign when $\Gamma = \sqrt{4/3}\Gamma_S(\phi)$, see Fig. 1(a). If the dependence of the electron hopping on the amplitude of the CNT oscillations is negligible, i.e., $\lambda^{-1} = 0$, the pumping coefficient $\eta(0) \propto \kappa\alpha^2\varepsilon(0)$ is determined by the sign of $\varepsilon(0)$. Such behavior is illustrated in Fig. 1(b). Figures 1(c) and 1(d) illustrate the cases of "positive" ($\alpha > 0$) and "negative" ($\alpha < 0$) electrostatic interaction, respectively.

Numerical analysis demonstrates that the predicted mechanical instability develops into pronounced self-sustained bending oscillations of the CNT resonator which, in its turn, result in a suppression of the DC electric current flowing between the STM tip and SC leads. This effect allows one to detect the predicted mechanical instability through the DC current measurement. A SQUID sensitivity to an external magnetic field can be achieved by using proposed nanomechanical Andreev device through the control of the Josephson phase difference by a magnetic flux.

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2.21 Photovoltaic effect generated by spin-orbit interactions

O. Entin-Wohlman, R. I. Shekhter, M. Jonson, A. Aharony

An AC electric field applied to a junction comprising two spin-orbit coupled weak links connecting a quantum dot to two electronic terminals is proposed to induce a DC 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 rejection-symmetry is broken. Its origin lies in the different fashion inelastic processes modify the rejection 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.

Electric weak links made of materials with strong spin-orbit interactions open a promising way to achieve spin-dependent transport of electrons. In the particular case of the Rashba spin-orbit coupling, the interaction can be tuned electrostatically or mechanically. This coupling obeys time-reversal symmetry which prevents spin splitting of electron transport in two-terminal junctions, in most cases eliminating the possibility to manipulate electronic conduction through Rashba weak links. Spin-orbit interactions do, however, have an effect on spin-polarized electrons in magnetic materials, and on electrons subjected to external magnetic fields. Here we propose that imposing a time dependence on the effective magnetic fields induced by the spin-orbit coupling offers an other means to destroy time-reversal symmetry of two- terminal junctions. In particular we predict that time-dependent Rashba interactions generate a DC electric current through unbiased junctions. Coherent electronic transport in response to periodic modulations of the shape of quantum dots or of other potential parameters of mesoscopic junctions has been attracting considerable interest following the seminal paper by Thouless, who showed that a slow periodic variation of the potential landscape may yield quantized and non-dissipative particle transport in unbiased junctions a phenomenon termed "adiabatic quantum pumping". Adiabatic pumping of spin currents resulting from periodic modulations of the shape of a spin-orbit coupled junction has been discussed as well, also as a result of temporal modulations of the Rashba interaction. However, the possibility to induce a DC particle current by such modulations in the absence of a bias voltage was not considered.

DC charge transport driven by time-dependent spin-orbit coupling is an alternative to the pumping of charge caused by tuning periodically the potential landscape of mesoscopic structures. It occurs in inhomogeneous junctions in which mirror reflection-symmetry is violated. In an unbiased junction no net current flows when the spin-orbit interaction is static, even in an asymmetric device: transport of electrons incident from the two opposite reservoirs is fully equilibrated. In fact, a static spin-orbit coupling, which results in a unitary evolution of the spinor wave-function, does not modify the DC transport. However, unitarity is destroyed by the time dependence that entails additional rejection processes due to inelastic tunneling. These in general differ for the two opposite directions in which electrons can be rejected from the junction, leading to uncompensated electronic transport. To elaborate on this general statement we refer to the device illustrated in Fig. 1: a quantum dot represented by a single level of energy is connected by spin-orbit coupled weak links to left and right reservoirs. Due to the Aharonov-Casher effect, the tunneling matrix elements attain unitary-matrix (in spin space) phase factors, denoted below by $V_L(R)$ for tunneling through the left (right) link. When these are time dependent, the rejection, say to the left direction, is then modified by factors of the form

$$\int^{t} dt'[V_L^{\dagger} te^{i(\epsilon-\omega+i\Gamma)(t-t')}V_L(t') + c.c.], \quad (1)$$

where Γ is the width of the resonance formed on the dot (using $\hat{=}1$). This form pertains to

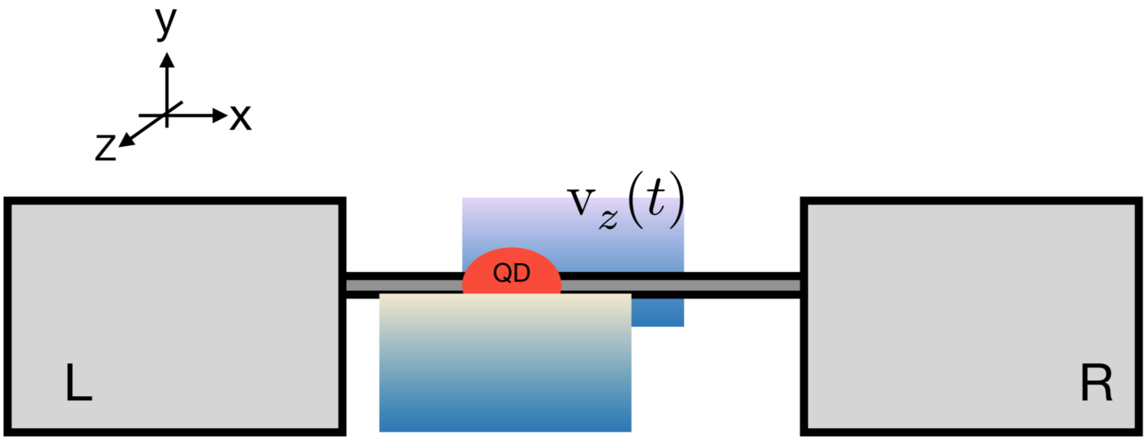

Figure 1: Illustration of the model system. A quantum dot, represented by a localized energy level, is attached by two weak links lying in the $x - y$ plane to two reservoirs, denoted L and R. An AC electric field along $\hat{z}$, whose amplitude oscillates with frequency Ω, induces a Rashba spin orbit interaction in the links.

tunneling from the left lead to the dot, accomplished at time $t0$, followed by a time evolution of the electronic wave-function on the dot during the time interval $t - t0$, and then tunneling back to the left lead at time t. One observes that in the static case, where $V_L^\dagger V_L = 1$, the integral yields the usual Breit-Wigner density of states on the dot, $2\Gamma/[(\omega - \epsilon)^2 + \Gamma^2]$. For a Rashba interaction that varies periodically with frequency Ω, the rejection comprises multiple inelastic channels with emission and absorption of $n\Omega$ energy quanta, which shift the resonance above and below ϵ. This complex modification of the rejection may differ for the opposite directions of the junction, leading to a net DC current. Below we show that such a difference can indeed result from the Rashba interaction when the lengths of the two weak links are not identical.

We have found that the spin-orbit (Rashba) interaction confined to an electric weak link, which when static has no significant effect on DC transport of two-terminal devices, may act as a source of DC currents when generated by a periodic electric field. This electric field renders the Rashba interaction time dependent, breaking the unitarity of the spin transmission by generating inelastic transmission channels. We have shown that this loss of unitarity appears as additional contributions to the backscattering. An estimate of the generated voltage drop in an open circuit suggests that it can be detected experimentally.

The effect we find is due to modifications of the probabilities for electron rejections, which are different for electrons approaching the junction from opposite directions; nonetheless, it is not related to quantum pumping. The origin of the latter are different time-dependent phases of the instantaneous rejection amplitudes, whereas a straightforward calculation of the instantaneous scattering matrix for the junction illustrated in Fig. 1 shows that the rejection amplitudes do not depend on time. This is because $V_L^\dagger(t)V_L(t) = 1$ due to the unitarity of the Aharonov-Casher phase factor. In our case, the rejections are modified by Aharonov-Casher phase factors at different times, and necessitate the inclusion of the inelastic dynamics on the dot.

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2.22 Superconducting edge states in a topological insulator

I. V. Yurkevich, V. Kagalovsky

Topological insulators (TI) have been a subject of intensive research in condensed matter physics [1]. Time-reversal symmetry (TRS) protects the existence of conducting edge states, each of them being a helical Kramers doublet (KD) with opposite spins propagating in opposite directions. TRS forbids a spin-flip backscattering within the same KD, but allows it between two different KDs. In a non-interacting system, a backscattering between different doublets generated by a disorder localises all edge states for even number of KDs but leaves at least one channel delocalized if the number of KDs is odd [2]. The former case then corresponds to a trivial insulator whereas the latter must be referred to as topological. The TRS argument [2] then states that the main distinction between topological and trivial insulators is the parity of the number of Kramers doublets. This is the conclusion reached on the basis of symmetries of the scattering matrix which is valid for non-interacting systems only. The effect of interactions on the edge states behavior under perturbations is of a great importance. It was studied intensively for systems with one or more KDs. One of the main conclusions of these studies was that an even number of KDs can be stabilised by interactions and remain conducting. On the other hand, to the best of our knowledge the existing experiments provide so far only evidence of the existence of 2D topological insulators with a single KD [3]. In our previous study [4] we have shown that in the clean system with N Kramers doublets there *always* exist $N-1$ relevant perturbations (either of superconducting or charge density wave character), which *always* open $N-1$ gaps. We have then investigated in detail the effect of disorder in the charge density wave regime, and showed that the interacting system with N Kramers doublets at the edge may be either a trivial insulator or a topological insulator for $N=1$ or 2, whereas any higher number $N>2$ of doublets gets fully localized by disorder pinning, irrespective of the parity issue.

In this paper, we consider the effect of disorder in the superconducting (SC) regime, when Josephson coupling is relevant in a clean system. After solving a Luttinger matrix equation for a multichannel Luttinger liquid constructed to study a topological insulator with N edge states [4] we find a corresponding scaling dimension. The SC regime a clean system is realized when $K\sqrt{1-\alpha_-} > \sqrt{1-\alpha_+}$, where the single-channel Luttinger parameter $K=\sqrt{(1+g_-)/(1+g_+)}$ and parameter $\alpha_\pm = g'_\pm/(1+g_\pm)$. All parameters are defined following standard nomenclature: $g_\pm = g_4 \pm g_2$ with coupling g_4 being an interaction strength between electrons moving in the same direction (right- with right-movers, and left- with left-movers), and g_2 is the interaction strength between electrons moving in the opposite directions within the same KD. The couplings with prime have similar meaning for inter-channel interactions.

The scaling dimension of the disorder perturbation in the SC regime is obtained according to Haldane criterion and is equal to

$$\Delta_{dis} = p^2 NK\sqrt{\frac{1+(N-1)\alpha_-}{1+(N-1)\alpha_+}}, \qquad (1)$$

where parity parameter p differentiates odd ($p=2$) and even ($p=1$) number N of edge states.

Now we present a phase diagram illustrating the stability of the SC regime. We follow [4] and consider only density-density interactions. We will focus now on the repulsive density-density interaction ($0<K<1$ and $0<\alpha_+<1$) and demonstrate that, nevertheless, the SC regime is possible. A conducting mode is robust in a SC regime if disorder is irrelevant. This region of existence is defined by disorder irrelevance, $\Delta_{dis} > 3/2$, and depends on the parity ($p=1$ and $p=2$ for even and odd channel number correspondingly).

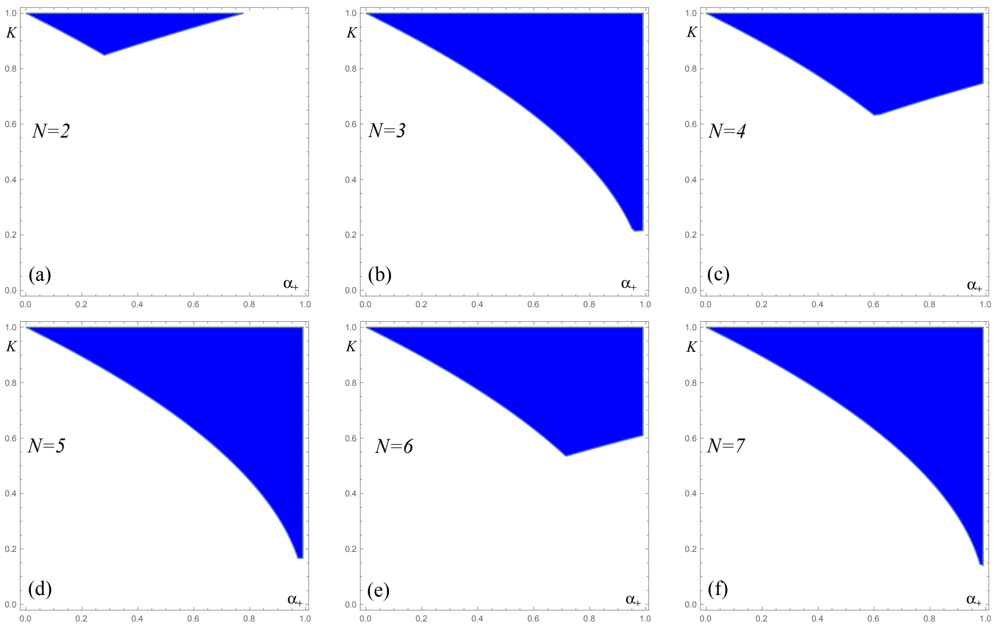

Figure 1: The phase diagram for a set of N Kramers doublets under repulsive density-density interaction. The blue regions represent stable SC regime.

We immediately observe that the disorder is much less relevant (large scaling dimension) for odd number of channels than for even as long as a number of channels N is not too large. As N is increasing, this difference disappears and only SC regime condition defines the stability of the mode, independent on parity of the number of channels. Figure 1 illustrates these properties.

The predicted in this paper edge superconductivity should be also measurable in experimental setups. The measurements carried out with a SQUID magnetometer must record dependence of a magnetic moment of the sample in a weak magnetic field. The edge current will not be able to expel the flux but it has to be observed and scale with temperature as a power law with non-universal, system dependent, exponent which is a distinct feature of the Luttinger liquid physics.

To summarize, we have studied a topological insulator with N Kramers doublets at the edge in the model of long range featureless interaction. We have shown that when a system is in the superconducting regime, the Josephson couplings open $(N-1)$ gaps and the disorder affects the only remaining centre-of-mass mode but, nevertheless, its effect depends on the parity the system had in the normal state. The scaling dimension and, therefore, the phase diagram are sensitive to the parity of the number of channels N for few channel case, and parity effect disappears for $N \geq 7$. We wish to stress that due to interchannel coupling even repulsive interactions may lead to a regime with dominant superconducting correlations.

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Chapter 3

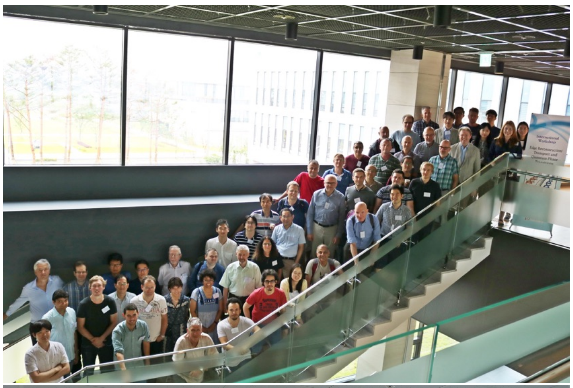
Details and Data

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 2019, 2020, and 2021, 228 (onsite: 107 & online: 121) 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 2019, 2020, and 2021, a total of 993 (onsite: 582 & online: 411) external workshop participants attended our 10 (onsite: 6 & online: 4) 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

- *Searching for Galactic Axions and Superconducting Devices with Quantum Efficiency*
  International Workshop: October 25 – 29, 2021
  Scientific coordinators: M. Lisitskiy, M. Fistul, Y. Semertzidis
  73 participants from 14 countries (including 43 participants from Korea) *Virtual Conference
- *IBS Conference on Flatbands: symmetries, disorder, interactions and thermalization*
  International Workshop: August 16 – 20, 2021
  Scientific coordinators: A. Andreanov, S. Flach, B.-J. Yang
  116 participants from 17 countries (including 75 participants from Korea) *Virtual Conference
- *Quantum Many-Body Dynamics: Thermalization and its Violations*
  International Workshop: May 24 – 28, 2021
  Scientific coordinators: J. D. Noh, Z. Papic, D. Rosa, L. Vidmar
  252 participants from 32 countries (including 61 participants from Korea) *Virtual Conference
- *Open Quantum Dynamics and Thermodynamics*
  International Workshop: March 22 – 26, 2021
  Scientific coordinators: P. Talkner, T. Ala-Nissila, J. N. Bandyopadhyay, J. Thingna
  141 participants from 36 countries (including 40 participants from Korea) *Virtual Conference
- *Frustrated Magnetism*
  IBSPCS-KIAS International Workshop: October 14 – 18, 2019
  Scientific coordinators: A. Andreanov, Y. B. Kim, S. Lee
  90 participants from 11 countries (including 63 participants from Korea)

- *Computational Approaches to Magnetic Systems*
  International Focus Workshop: August 26 – 28, 2019
  Scientific coordinators: K. Kim, B. Kim, A. Go, H. Park, C. Franchini, B. I. Min
  67 participants from 13 countries (including 45 participants from Korea)
- *Physics and Applications in Nanoelectronics and Nanomechanics*
  IBSPCS-KIST International Focus Workshop: August 19 – 21, 2019
  Scientific coordinator: C. Kim
  64 participants from 9 countries (including 53 participants from Korea)
- *Recent Advances in Topological Photonics*
  International Workshop: June 17 – 21, 2019
  Scientific coordinators: D. Leykam, Z. Chen, A. Szameit
  81 participants from 11 countries (including 50 participants from Korea)
- *Spintronics and Valleytronics of Two-dimensional Materials*
  International Workshop: May 20 – 24, 2019
  Scientific coordinators: M. Glazov, S. Höfling, I. Savenko
  70 participants from 12 countries (including 43 participants from Korea)
- *Exotic Magnetic Phases in Quantum Many-body Systems*
  Mini-Workshop: April 23, 2019
  Coordinators: A. Go , E.-G. Moon
  39 participants from 3 countries (including 37 participants from Korea)

Future overview

- *Condensed Matter Solitons*
  International Workshop: June 29 – July 1, 2022
  Scientific coordinators: S. Kim, S. Chung, M. J. Park, Y. Shin, J.-H. Kim
- *Computational Approaches to Magnetic Systems (CAMS-2022)*
  IBSPCS-APCTP International Workshop: August 24 – 26, 2022
  Scientific coordinators: C. H. Kim, C.-J. Kang, S. Kim, H.-S. Kim, I. Di Marco, A. Go, B. Kim
- *Flatbands and Correlated States in Quantum Matter*
  International Workshop: August 29 – September 2, 2022
  Scientific coordinators: A. Andreanov, J.-W. Rhim, T. T. Heikkilä
- *Advances in The Physics of Topological and Correlated Matter*
  IBS-APCTP Conference: September 19 – 23, 2022
  Scientific coordinators: H. W. Yeom, T. W. Noh, S. Flach, Y. Bang
- *Dynamics Days Asia Pacific DDAP12*
  International Workshop: October 31 – November 4, 2022
  Scientific coordinators: S. Flach, J. D. Noh, B. Kahng, H. Park

3.1.2 Advanced Study Groups

- *Computational approaches to correlated systems: Applications to diverse materials*
  Advanced Study Group: Jul. 12 – Jul. 16, 2021, Feb. 14 – Feb. 18, 2022, and video conferences
  Convener: S. Kim (Kyungpook National University, Korea)
  Members: A. Go, B. Kim, H. C. Park, H. Kim, S. Y. Park, M. Kim, C. J. Kang, J. Han, K. Kim, H. C. Choi, C. H. Kim
- *Incommensurately stacked atomic layers*
  Advanced Study Group: Jun. 17, Jul. 12 – Jul. 14, 2021

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

- *Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links*
  Advanced Study Group: Video conferences
  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, I. Krive, H. C. Park, D. Radić
- *Deep Learning in Quantum Phase Transitions*
  Advanced Study Group: Video conferences
  Convener: V. Kagalovsky (Shamoon College of Engineering, Israel)
  Members: A. Andreanov, I. Eremin, M. Fistul, A. Go, W. S. Lee, E.-G. Moon, T. Ohtsuki, M. Ortuño, D. Saad, K. Slevin, I. Yurkevich, A. Fedorov, S. Kravchenko
- *Functional Spin-Active Mesoscopic Weak Links*
  Advanced Study Group: Jan. 27 - Feb. 27, Aug. 5 - Sep. 12, and Oct. 28 - Nov. 28, 2019
  Convener: R. Shekhter (University of Gothenburg, Sweden)
  Members: A. Aharony, O. Entin-Wohlman, L. Gorelik, M. Jonson, C. Kim, I. Krive, H. C. Park, D. Radić, J. Suh

Future overview

- *Computational methods in transition metal compounds: correlations and magnetism*
  Advanced Study Group: Jul. 18 – Jul. 22, Dec. 19 – Dec. 21, 2022, Feb. 13 – Feb. 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: May 15 – Jul. 14, Jul. 15 – Aug. 30, 2022, Nov. 22, 2022 - Jan. 21, 2023
  Convener: P. Moon (New York University in Shanghai, China)
  Members: M. 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. 19 – Jul. 16, 2022
  Convener: V. Kagalovsky (Shamoon College of Engineering, Israel)
  Members: A. Andreanov, I. Eremin, M. Fistul, A. Go, W. S. Lee, E.-G. Moon, T. Ohtsuki, M. Ortuño, D. Saad, K. Slevin, I. Yurkevich, A. Fedorov, S. Kravchenko
- *Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links*
  Advanced Study Group: Jan. 29 – Feb. 27, Jul. 25 – Aug. 26, Nov. 07 - Dec. 09, 2022
  Convener: R. Shekhter (University of Gothenburg, Sweden)
  Co-Convener: J. Suh (KRISS, Korea)
  Members: A. Aharony, O. Entin-Wohlman, M. Jonson, L. Gorelik, D. Radić, C. Kim, H. C. Park

3.1.3 Workshop Reports

Searching for Galactic Axions and Superconducting Devices with Quantum Efficiency
Scientific coordinators: Mikhail Lisitskiy, Mikhail Fistul, Yannis Semertzidis

The main aim of the workshop was to bring together and match the efforts of world leading scientists and young researchers working in two separate and challenging fields connected by the emergence of commonly needed technology. Searching for dark matter Axions (the scale of the Universe) and quantum information technology (the microscopic and mesoscopic scales) allowing to develop and realize quantum photon detectors capable of detecting extremely weak electromagnetic signals in the microwave region; discuss the current results, future perspectives and exchange new ideas in quantum metrology with application to axion dark matter search. In spite of severe time constraints for this on-line event around forty local and foreign scientists participated in the Workshop. During the Workshop twenty scientific talks have been delivered by invited speakers (2 from South Korea, 16-Europe, 1-USA, 1-Australia). The talks focused on recent advances in the detection of the dark matter Axions carried out in the framework of special research programs established in Europe, USA, Australia and South Korea, i.e. ADMX experiment, QUAX, MADMAX Haloscopes, CAPP, etc., and the detection of single microwave photons with high efficiency. In particular, several invited talks were dedicated to the research activity in the framework of the SUPERGALAX HORIZON 2020 FETOPEN Project. In the latter area of research various novel approaches were recognized:

- Coherent superconducting interacting qubits networks
- Josephson parametric amplifiers based on superconductors with high kinetic inductances
- Josephson traveling wave parametric amplifiers
- microwave single photon counters based on a Josephson tunnel junction biased in the MQT (macroscopic quantum tunneling) regime
- coherent magnetic excitations
- entangled microwave photons in ac driven Josephson junctions

and how these approaches can be used in the dark matter Axion experiments. The colloquium was delivered by Prof. Michael Tobar who spoke about the dark matter Axion studies (experiments and theory) at the University of Western Australia. The participants representing two scientific communities actively discussed and exchanged novel ideas. We anticipate that these discussions will lead to long-term research projects between various groups. We also received positive feedback from several participants about the quality of organization of the Workshop. Overall, we met the main goals of the workshop and there is a strong interest in holding an in-person event on the same topic in the future.

IBS Conference on Flatbands: symmetries, disorder, interactions and thermalization
Scientific coordinators: Alexei Andreanov, Sergej Flach, Bohm-Jung Yang

The main aim of the event was to bring together experts and to discuss recent advances and developments in the field of flatband physics. This is an actively developing area with new experiments and theoretical results emerging regularly, especially related to flatband superconductivity and 2D materials. The conference was focused on the topics we considered as key directions for the area:

- Finetuning and perturbations of flatbands
- Effects of symmetries
- Many-body interactions
- Applications

With these key topics, we managed to invite 17 speakers from Europe and Asia (due to time zone constraints). The conference has also hosted the IBS Colloquium on flat band physics, delivered by Daniel Leykam, a former IBS Young Scientist Fellow and a member of IBS PCS, presently a senior research fellow at National University of Singapore.

As the outcome of the Conference several key questions have emerged:

- Understand in more details the interplay of superconductivity and flatbands
- Understand the possibility and properties of superconductivity in (periodically) driven systems
- Understand macroscopic degeneracies/flatbands in driven systems and non-Euclidean geometries, that are expected to have unusual properties
- Necessity for developing a generic framework to construct flatband models and understand their response to perturbations, especially interactions

The IBS Conference was highly successful in our opinion. There were more than 100 participants with a daily number of participants fluctuating around 60 in the Zoom channel. Most of the talks were recorded and are available on the PCS Youtube channel. Slides of (some of) the talks are available on the Conference webpage. A large number of the speakers and participants praised IBS for the running of this meeting, stressing how important it is to reconnect among the flatband research community during these harsh pandemic times. Finally several collaborations have emerged as a result of the Conference.

Quantum Many-Body Dynamics: Thermalization and its Violations
Scientific coordinators: Jae Dong Noh, Zlatko Papic, Dario Rosa, Lev Vidmar

The main goal of the event was to bring together leading international experts in the broad topic of thermalization and its violations in quantum many-body systems, in order to discuss and show the most recent theoretical results in this field. This is a very active area of research which is recently receiving more and more interesting inputs from newly developed experimental techniques. In turns, strong efforts have been devoted in developing simple theoretical models able to reproduce and explain such experimental results. Before the organization of the workshop we recognized the following key topics, which we decided to address extensively in separate scientific sessions.

- Many-body quantum chaos and scrambling
- Thermalization
- Quantum many-body scars
- Many-body localization

Having recognized the strategic areas listed above, we were able to invite 13 international speakers (both from Asia and Europe). On top of that, we had the opportunity to invite Prof. David Logan from Oxford, who delivered a colloquium on the topic of many-body localization in Fock space. Among the outcomes of the workshop we mention

- The necessity to develop new and more powerful numerical tools to find and characterize low entanglement states at infinite temperature. These states are particularly relevant in order to find exceptions to the Eigenstate Thermalization Hypothesis.

- Develop and understand the connections between quantum many-body scars and fracton dynamics.
- Develop new numerical and analytical tools to study many-body localization in the thermodynamic limit.
- Develop and study in more details the classical limit of the Out-Of-Time-Order correlators as a probe of quantum chaos.

Another goal of the workshop was to increase the international visibility of the newly established PCS team "Quantum Chaos in Many-Body Systems", led by Dario Rosa.

Overall, the results of the workshop are satisfactory: roughly 150 applicants registered to the workshop, with a daily participation of 100 participants in the Zoom channel. All the talks are recorded and freely available on the PCS YouTube channel. In addition, after the workshop we received some manifestation of interests from the participants to join PCS-IBS in the near future. At the same time we have had the opportunity to start some collaborations between the group Quantum Chaos in Many-Body Systems and some other research groups, both in Europe and in Asia. We hope that this collaborations will bring to intriguing new results in the future.

Open Quantum Dynamics and Thermodynamics
Peter Talkner, Tapio Ala-Nissila, Jayendra Nath Bandyopadhyay, Juzar Thingna

The main aim of the workshop was to bring together international experts in the rapidly growing fields of open quantum systems and quantum thermodynamics. It focused on the recent advances in the numerical approaches to treat quantum many-body open systems, strong-coupling non-Markovian dynamics, quantum synchronization, quantum machines, and fluctuation theorems. The workshop gave the Korean researchers a platform to showcase their recent results and aimed at developing and strengthening international collaborations. The colloquium was delivered by Prof. Jian-Sheng Wang who spoke about weak-to-strong coupling quantum master equations and their application to quantum transport.

During the course of the workshop several key target areas were recognized:

- Developing robust numerical approaches to go beyond weak coupling master equations and to develop the corresponding thermodynamics.
- Extending thermodynamic framework to realistic scenarios like to calculate work output from windmills and going beyond the zero-viscosity limit to consider turbulent air flows.
- To find universal bounds for quantum finite time heat engines and elucidate on the interplay between collective phenomena and engines performance.

Due to the ongoing COVID pandemic the workshop was restricted to an online mode with 10 invited speakers limited to Asia (India: 2, S. Korea: 2, Singapore: 2, China: 2, Iran: 1, and Armenia: 1). We received an overwhelming response with 115 participants (Asia: 62, Europe: 36, North America: 7, South America: 6, and Africa: 4), 38 of which presented posters, and 5 gave a contributed talk. All our talks are available on the PCS' YouTube channel. The poster session turned out to be a fun interactive session hosted on Gather Town, a virtual platform on which participants moved around and interacted via their avatars. Our media partner Entropy (MDPI) sponsored a best contributed talk award that was presented to Dr. Marti Perarnau-Llobet for his talk on "Optimal cycles for finite-time Carnot engines".

We received extremely positive feedback from several participants about the smooth organization and the use of Gather Town for poster presentations. The international participants were impressed by the local research and this helped improve our visibility internationally. Several young participants expressed a strong interest in working with PCS, IBS in the future.

Overall, we met the main goals of the workshop and there is a strong interest in holding a larger in-person event on the same topic in the future. The workshop highlighted some of the recent developments in the fields of open quantum systems and quantum thermodynamics and showcased the contributions of Korean researchers. Despite being online, the participants actively participated which led to interesting discussions that took place in a friendly environment. The discussions led to several new ideas or proposals taking shape and we anticipate these results into long-term research projects between various groups.

Frustrated Magnetism
Scientific coordinators: Alexei Andreanov, Yong Baek Kim, SungBin Lee

The aim of the workshop was to bring together people from frustrated magnetism community and related areas, to let them interact, discuss the open problems and eventually develop new collaborations. The workshop hosted 63 invited speakers and participants (of which 11 represented PCS), representing 8 countries. The majority of external (non-PCS) participants were from Korea (35), followed by US(6), Canada(3), Japan(3), France(2), Germany(1) and Hungary(1). The workshop had more focus on theory with 18 theoretical talks vs 7 experimental ones, however many theoretical presentations were addressing experimental issues. 11 contributed posters were presented by the participants.

Frustrated magnetism has around thirty years of history but is still an active topic of research. Frustrated magnets feature competing interactions - due to their range, system geometry or both - which suppress the naive ordering and produce exotic or macroscopically degenerate groundstate. These might be unstable under perturbations/sub-dominant interactions inevitably present in real materials leading to many interesting phenomena. Reviewing the current state of the field, identifying and discussing the key open problems, and our progress in solving them was the motivation of the workshop. The major topics of the workshop included:

- properties of novel magnetic materials and new magnetic orders
- quantum spin liquids
- spin-orbit coupled magnetism
- disordered/glassy magnetic systems

Connections to topologically protected phases and physics of non-Hermitian systems were also explored. The key open problems discussed during the workshop:

- Experimental signatures of quantum spin liquids in materials: the complex nature of the quantum spin liquid (QSL) - a quantum state of matter with no conventional order parameter - makes it difficult to devise clear experimental markers of this phase. Simple theoretical models are complicated by presence of additional interactions in real materials, that might suppress the QSL. It is therefore of prime importance to develop realistic models of the candidate materials, and come up with experimentally observable quantities capable of capturing the presence or proximity to the QSL phase. The discussions at the workshop suggested that refining the experimental techniques and advancing the theory will likely allow to unambiguously detect a QSL in experiments in the coming years.
- Effects of disorder and external field in frustrated magnets: Many frustrated magnets show freezing at low temperature - a characteristic feature of disordered/glassy systems

- in absence of conventional sources of glassiness. Several scenarios explaining such behaviour have been suggested already and new ones were presented at the workshop. The reverse problem - how various types of disorder affect the magnetic systems - is also important, and was discussed based on several examples.

- Similarly response of frustrated systems to the application of magnetic field is a non-trivial problem, especially for the QSL, where it could be one of the potential markers of the presence of the quantum spin liquid phase.
- Frustrated spin-orbit magnets offer new models with interesting properties due to the increased number of degrees of freedom.
- Magnons in frustrated magnets, which might have interesting properties or can be used as conventional simulators of other physical models.
- Understanding dynamical response of quantum and classical frustrated magnets.

These results and the discussions during the workshop indicate that these problems would remain at the focus of the future research in frustrated magnetism and provided an overview / perspective of the current state of the field of frustrated magnetism. From the practical side, the participants have appreciated the long 2h breaks for lunch and the coffee breaks, which provided opportunities for discussions, that mostly happened in the PCS lounge. The talks were typically interactive with many questions.

In summary the main goals of the workshop as were stated in the proposal have been achieved, and the feedback received from the participants so far was highly positive, especially regarding the organisation and the support by the Visitors Program.

Computational Approaches to Magnetic Systems
Scientific coordinators: Kyoo Kim, Bongjae Kim, Ara Go, Hyowon Park, Cesare Franchini, Byung Il Min

The description of magnetic system is not easy task to do, because of the complex origin of magnetism where correct description of both itinerant interaction and localized interaction of electrons is needed. Recent advance of computational ability made computational/numerical approaches as 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 own strengths and weaknesses depending on the material-specific characteristics.

This workshop have been planned to bring together the experts in each area, thereby providing a platform to discuss the frontier issues. Special attention is paid to provide the network for the young researchers with different technical backgrounds, and promote the further collaborations. Based on these basic ideas, our workshop has unique characteristics. Unlike existing workshops for diverse materials, we focused on specifically magnetic systems, and we spared lots of talks on the methodologies which describe various scales of magnetism in the condensed matter systems. Specially in this workshop, recent development and application of DFT+DMFT scheme, temporal evolution of magnetism within TDDFT, various scale consideration of magnetism, and state-of-the-art computation approaches adopting machine learning, and/or many body perturbation techniques. These methodological subjects are well-incorporated in the material-specific topics, and the audiences as well as the speakers can acquire in-depth knowledge in the field.

The international workshop "Computational Approaches to Magnetic Systems" was held at the Center for Theoretical Physics of Complex Systems (PCS), Daejeon during August

26 - 28, 2019. Special intention is focused on the gathering of young and active researches to promote the active discussions and collaborations. About 50 participants including 6 scientific coordinators and 18 speakers about diverse topics in magnetism are gathered in CAMS. Invited speakers are from Austria, US, China, Japan, Vietnam, and Korea and gave a talk about the description on magnetic systems with various computation methodologies: DFT, DMFT, field theory, etc. Participants including students are encouraged to prepare for poster session and had a chance of discussion and future collaboration with speakers and professors. Total 11 posters are presented.

A nice opening remark of Prof. Sergej Flach, the director of PCS IBS, regarding the history, status and the activity of IBS and also the vision of Korean Physics society, was the start of workshop. Afterward, professor Byung Il Min from physics department of POSTECH, one of scientific coordinator gave an opening talk about the history of research on magnetism, and the tools for describing magnetism: a rendezvous of itinerant and local physics. He also encourages the young physicist with Confucius teaching regarding the attitude of research.

Soon after, the main part of workshop follows.

The list of talks follows:

Day1

- Jan Tomczak (TU Wien, Austia): Realistic many-body theory of Kondo insulators: Renormalizations and fluctuations in Ce3Bi4Pt3.
- Yue Chen (Univ. of Hong Kong, China): Molecular dynamics study of phonon scattering in partially disorder system.
- Hiroshi Shinaoka (Saitama Univ., Japan) : Sparse sampling approach to susceptibility calculations in dynamical mean-field theory.

Day2

- Andriy Nevidomskyy (Rice Univ., USA): Revealing the emergent spinon Fermi surface and novel nematic quantum spin liquid in a spin-1 square lattice.
- Eun-Gook Moon (KAIST, Korea): Unconventional quantum phases and criticalities.
- Alessandro Toschi (TU Wien, Austria): Osmates on the verge of a Hund's-Mott metal-insulator transition: The different fates of NaOsO3 and LiOsO3.
- Hosub Jin (UNIST, Korea): Spin-orbital entangled $J_{eff} = 1/2$ states in transition metal compounds.
- Hanghui Chen (NYU Shanghai, China): Emergent phenomena in correlated oxides close to metal-insulator transition.
- Choong Hyun Kim (IBS-CCES & Seoul Nat'l Univ., Korea): Correlated topological phases in transition metal compounds.
- Jaedong Lee (DGIST, Korea): Valley magnetic domain as a pathway to the valleytronic current processing.
- Minh-Tien Tran (Vietnam Acad. Of Sci. and Tech., Vietnam): Exotic state in a strongly correlated electron system.

Day3

- SungBin Lee (KAIST, Korea): Topological d-wave superconductivity in lacunar spinel GaTa4Se8.
- Xin Wang (City Univ. of Hong Kong, China): Application of reinforcement learning to quantum control problems.

- Kwan-Woo Lee (Korea Univ., Korea): A noncentrosymmetric compensated half-metal hosting pure spin Weyl points and nexus fermions.
- Gang Li (ShanghaiTech Univ., China): Parquet equation: a self-consistent many-body theory in both single- and two-particle level.
- Jeongwoo Kim (Incheon National Univ., Korea): Tailoring spin orientation via manipulating electronic structure in two-dimensional magnet CrI3.
- Sooran Kim (Kyungpook National Univ., Korea): Apical ion dynamics-modulated in-plane transport properties of cuprate superconductors.

From the scientific point of view, we believe the workshop has been a great success. The overall atmosphere was hot by intensive discussions for every talk, and often the discussions continued during coffee breaks and lunch time. In every break time, the participants actively gathered in mini groups and discussed lively. During the poster session, with nice welcome reception in the first day, enthusiastic communications were made between students and speakers. Prolonged discussions were made among some participants after the workshop, and collaborations among the participants are already initiated.

The concept of young people- and discussion-oriented workshop is often practiced in USA and Europe but not so common on Korea. Here, we think we set a nice example. The feedbacks of the participants were very positive, and many speakers have asked for the notice for the "Computational Approaches to Magnetic Systems" workshop next year. 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.

The workshop could not be finished such smoothly without the help and coordination of administrators of the visitor and workshop program, PCS IBS. During the preparation, Dr. Dominika Konikowska and Ms. Gileun Lee checked every details of workshop. We appreciate the perfect coordination of them.

After the workshop, scientific organizers had small discussions on the future direction of the workshop (vision). There is a demand for the focus workshop or sessions on the one or two special topics of computational methods, for instance, numerical renormalization group technics, green function based methodologies, or on specific systems such as superconductivity and magnetic fluctuations or magnetic van der Waals materials. Implementation of this idea can be a possible expansion of the workshop with longer timeline.

Physics and Applications in Nanoelectronics and Nanomechanics
Scientific coordinator: Chulki Kim

The PCSIBS-KIST international focus workshop on "Physics and Applications in Nanoelectronics and Nanomechanics" took place at the IBS Center for Theoretical Physics of Complex Systems (IBS-PCS), Daejeon on August 19-21, 2019. It was organized by Advanced Study Group in IBS-PCS and funded by the IBC-PCS, KIST, KRISS, and KAIST. It was scientifically coordinated by Chulki Kim (KIST). It focused on the topic of physics and applications in nanoelectronics and nanomechanics by addressing the recent achievements in theoretical and experimental studies of the field.

There have been 14 invited talks, and 8 posters during the workshop on the topics of

- Systems with coherent nanoelectromechanical(NEM) transductions
  - Superconducting transmons coupled to surface acoustic waves
  - Quantum sensing with NEMS
  - Superconducting "Cooper pair Box" coupled to a shuttle vibrons

  - Flexural vibrations coupled to a single-molecule electrons
  - Mechanical testing of superfluid
- Devices with non-coherent NEM coupling
  - Dissipative cavity electro-mechanical system using semiconducting InAs nanowire
  - NEM lattices for on-chip phononic devices operating at MHz frequencies
  - Hexagonal boron nitride heterostructures for near ultraviolet light emission
  - Sound frequency analysis using biomimetic membrane
- Spin-active hybrid device
  - Stain-mediated mechanical control of spin in semiconductor heterostructures
  - Spintro-mechanics of magnetic shuttle devices
  - Electron-spin resonance and surface acoustic waves in suspended graphene
  - Theoretical study of transport in SOI-active electric weak links
  - Thermal breakdown induced by mechanical heat transduction

Nanoelectromechanical systems (NEMS) have been studied for decades, with interest increasing recently because of growing scientific and commercial applications. These are electromechanical systems operated in their resonant modes with dimensions in the submicron. In this regime, they come with high fundamental resonance frequencies, diminished active masses, and high quality factors of resonance significantly higher than those of electrical resonant circuits. These attribute collectively make NEMS suitable for a multitude of technological application as well as fundamental studies on physics.

At the heart of the workshop lie sharing thoughts and ideas on NEMS and discussing where this research field goes in the future. NEMS are expected to open up investigations of phonon mediated mechanical processes and of the quantum behavior of mesoscopic mechanical systems. This workshop provided a balanced introduction of NEMS by discussing the prospects and challenges in this rapidly developing field and outlined interesting studies and experiments. The recent NEMS studies were focused on coherent and non-coherent nanoelectromechanical transductions and couplings. In addition, the cutting edge NEMS applications for quantum bit manipulation and ultra-sensitive mass sensing as well as fundamental researches on spin-active hybrid devices emerged. Finally, we note that quantum nanomechanics is the emerging field which pertains to the mechanical behavior of nanoscale systems in the quantum domain. These studies of coherence and tunneling effects in any quantum systems lent themselves to relevant questions in quantum measurements. As seen in the workshop, most of the important achievements and issues related to NEMS were deeply shared and discussed out during the workshop. And it was also noted that in spite of its obvious importance, however, many experiments on quantum nanomechanics still await proper and complete physical realization. This workshop brought established researchers from all over the world working on physics and applications in nanoelectronics and nanomechanics and created a unique opportunity to stimulate discussions on their most recent achievements. More than 70 participants from South Korea, USA, Germany, Sweden, Japan, Croatia, Israel and Ukraine took part in this workshop. And we expect that the continuity of this workshop will bring improvement and incremental growth in this research field by providing more opportunities for researcher to meet, interact and exchange innovative ideas in the future.

Suggestions: More flexibility in financially supporting invited speakers would be helpful to organize the workshop effectively.

Acknowledgements: We would like to thank the IBS for Theoretical Physics of Complex System for its support and hospitality. Especially, we would like to thank Dr. Dominika Konikowska and Ms. Gileun Lee at PCS-IBS for their kind assistance and friendly support

in organizing the workshop. We are also grateful to the PCS-IBS, KIST, KRISS, and KAIST for their financial supports.

Recent Advances in Topological Photonics
Scientific coordinators: Daniel Leykam, Zhigang Chen, Alexander Szameit

The main aims of the workshop were to discuss recent progress in bringing the concept of topological protection to novel photonic systems 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 topological lasers, integration topological edge modes with quantum optical effects, non-Hermitian topological phases, nonlinear effects in topological photonics, and novel implementations of topological photonic crystals such as 3D photonic topological insulators. In addition, the program featured several invited talks from experts in related fields, covering topics ranging from surface waves of anisotropic optical media to phononic crystals. A highlight of the workshop was the colloquium talk by Prof. Franco Nori on quantum simulation using superconducting electronic circuits.

The workshop benefited from a diverse cast of 72 invited speakers and participants representing 11 countries, including 15 from PCS. The majority of external participants were from Korea (about 20), followed by China and Japan (8 each). The remainder came from further afield (Europe, USA, 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 (14) and theoretical (15) talks, and good participation in the poster session (11 contributed posters).

Many participants appreciated the long (2 hour) lunch breaks because they provided a good opportunity for informal discussions. During this time several key open problems for the field were identified and debated:

- The non-Hermitian skin effect (localization of all eigenfunctions in certain non-Hermitian lattices) has now been the subject of several theoretical studies, but still awaits experimental verification. Ring resonators with lossy or active coupling seems to be a promising platform.
- The existing topological band theory for non-Hermitian systems appears to be incomplete.
- An important limitation of existing topological lasers is the potential for detrimental noise to be protected in addition to the topological protection of the lasing mode.

It is clear that non-Hermitian topological photonics is likely to continue to be a highly active area of research for the next few years, and closer integration of topological photonics with quantum optics is anticipated.

Following the workshop, a journal has contacted us with interest in hosting a special issue related to the topics presented at the workshop. In hindsight, it would have been preferable for us to contact them before the workshop to potentially arrange sponsorship (e.g. donation of a poster prize). We suggest the coordinators of future workshops should be reminded of these kinds of opportunities.

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. There is strong interest in holding another meeting on this topic in the future.

Spintronics and Valleytronics of Two-dimensional Materials
Scientific coordinators: Mikhail Glazov, Sven Höfling, Ivan Savenko

The main aim of the workshop was to discuss the frontiers of studies of two-dimensional materials, including graphene, transition metal dichalcogenides, 2D topological insulators with the emphasis on the spin and valley properties of these materials and on the light-matter coupling effects. The discussion of the recent research with the world-leading experts, as well as developing and strengthening collaboration between the theoretical and experimental research groups was also among the goals.

The topics of the workshop included the basic properties and spin/valley physics in two-dimensional semiconductors, exciton-polaritons in artificial lattices, photoelectric effects including photon-mediated superconductivity, photon drag and photogalvanic effects, physics of the hybrid Bose-Fermi systems, Weyl semimetals, etc. The workshop brought together over 30 experts from Europe, USA, Russia, Japan, Korea.

There was a good balance (45% to 55%) between the experimental and theoretical talks, many of the presentations contained both experiment and theory.

Several key scientific problems where identified and discussed:

- Physics of electron and exciton localization/delocalization in Moire superlattices;
- Metal/insulator/superfluid transition for disordered bosons;
- Role of anomalous velocity in the valley Hall effect for excitons and exciton-polaritons;
- Realization of polariton topological insulator;
- Photoresponse of topologically nontrivial systems.

We have received extremely positive feedback from different workshop participants. For researchers working on two-dimensional materials, topological insulators, exciton-polaritons in artificial potentials, the Center for Theoretical Physics of Complex Systems (PCS IBS) is now a place to establish new collaborations. The overall visibility of the local research done in this field substantially grows. Some of the young participants expressed a strong interest in working with PCS IBS in the future.

To conclude, the main goals of the workshop were successfully fulfilled. The Workshop demonstrated a growing interest of the scientific community to novel two-dimensional systems and materials. The workshop took place in a good atmosphere of friendly but still deep and sometimes heated scientific discussion. The plans for future collaboration were discussed.

Exotic Magnetic Phases in Quantum Many-body Systems
Scientific coordinators: Ara Go, Eun-Gook Moon

The recent discovery of Majorana modes and exotic excitations boosted research interests in quantum many-body systems. This half-day mini-workshop aimed to gather researchers who are actively working in this field and to provide them opportunities for sharing ideas and having inspiring discussions. The workshop brought 31 participants including speakers, from Korea, Japan, and the USA.

We hosted ten talks which cover various subjects from the methodology and numerical calculations on quantum many-body systems. Many speakers talked about Kitaev quantum spin liquids in α-RuCl3: how to understand exotic behaviors of quantum phase transitions in Kitaev systems, how to derive a microscopic model describing practical systems, and numerical techniques to handle many related degrees of freedoms in the relevant models. The quantum spin ice system, topological superconductivity, exotic excitations in a quantum spin chain, higher order topological insulator, and realization of quantum metrology were also discussed. The excellent presentations stimulated discussions deepening understanding of the subject and shined the future direction to push further studies.

The eighteen participants joined the workshop dinner and continued the discussion on many aspects, including scientific topics and future development of this event. Overall, the workshop successfully brought the researchers and encouraged them to have fruitful discussions. Many of participants were excited by the event and suggested promoting the mini-workshop a regular event to support close networking between the researchers in this field. It will bring significant impact to the community, providing pioneering synergy between scientists who are working in quantum many-body systems.

3.1.4 External Cofunding of Workshops and Seminars

- *Frustrated Magnetism*
  International Workshop: October 14 – 18, 2019
  – 28% of the workshop budget contributed by the KIAS (Korea Institute for Advanced Study, Korea) and DIME (Daejeon International Marketing Enterprise, Korea)
- *Computational Approaches to Magnetic Systems*
  International Workshop: August 26 – 28, 2019
  – 64% of the workshop budget contributed by the ICTP (International Centre for Theoretical Physics, Italy), KSNU (Kunsan National University, Korea), MPK (Max Planck POSTECH / Korea Research Initiative), and DIME
- *Physics and Applications in Nanoelectronics and Nanomechanics*
  International Workshop: August 19 – 21, 2019
  – 59% of the workshop budget contributed by the KIST (Korea Institute of Science and Technology, Korea) and KRISS (Korea Research Institute of Standards and Science, Korea)

3.1.5 Advanced Study Group Reports

Computational approaches to correlated systems: Applications to diverse materials
Convener: Sooran Kim

Our Advanced Study Group (ASG) had an active plan throughout the year 2021, during which its activities followed the approved research plan and timeline. However, we faced a COVID-19 catastrophic situation throughout the whole world. We found a way to collaborate with ASG members and external collaborators. Collaborative efforts during this year were complemented by internet contacts among ASG members and external collaborators. Several interesting studies are ongoing on low-dimensional spin-orbit systems and Hund's metal physics. We want to further pursue this research line and search for proper candidate materials. We share ideas to establish a new framework in ubiquitous systems. The two most significant scientific topics, in our opinion, are the following:

Collaborative topic:

- Hund's metal physics:

  1. Manipulating emergent properties of Hund metal : SrRuO3-SrTiO3 heterostructure
  2. Hund's metallicity and van Hove singularity

3. Hundness and Mottness in single layer ruthenates
4. Hidden Hund's physics in the infinite-layer nickelates

- Spin-orbit entangled systems, Correlated materials, Topological materials:
  1. Dynamical mean-field theory for spin-orbit coupled materials, development and implementation of numerical algorithms for quantum embedding theory
  2. Transition metal oxide heterostructures and superlattices, Ferroelectric and multiferroelectric oxides, Optical properties of correlated systems

Meetings at PCS:

- Toward to reliable AI for scientific computing
  S. Kim, B. Kim, H.-S. Kim, S. Y. Park, M. Kim, K. Kim, C. H. Kim, A. Go , J.-H. Han, and H. C. Park, H. Yoon, 15.07.2021
- Joint meeting with ASG "Incommensurately stacked atomic layers"
  S. Kim, B. Kim, H.-S. Kim, S. Y. Park, M. Kim, K. Kim, C. H. Kim, A. Go , J.-H. Han, and H. C. Park, 12.07.2021 (12.07.2021 - 14.07.2021)

Seminars and meetings via video conference:

- Diagrammatic Monte Carlo solutions to longstanding problems of strongly correlated fermions
  A. Kim, S. Kim, B. Kim, H.-S. Kim, S. Y. Park, M. Kim, C. H. Kim, A. Go, H. C. Choi, C. J. Kang, K. Kim, J.-H. Han, and H. C. Park, 08.10.2021
- Computational study on the materials for rechargeable batteries using first-principles calculation
  D.-H. Seo, S. Kim, B. Kim, H.-S. Kim, S. Y. Park, C. H. Kim, A. Go, C. J. Kang, J.-H. Han, and H. C. Park, 10.09.2021
- Magnetic excitation and thermal properties of proximate Kitaev systems under an in-plane magnetic field
  S. Kim, B. H. Kim, B. Kim, H.-S. Kim, S. Y. Park, M. Kim, K. Kim, H. C. Choi, C. H. Kim, A. Go, C. J. Kang, J.-H. Han, and H. C. Park, 30.07.2021
- Freestanding crystalline oxide membranes and heterostructures
  S. Kim, S. S. Hong, B. Kim, H.-S. Kim, S. Y. Park, M. Kim, K. Kim, H. C. Choi, C. H. Kim, A. Go, C. J. Kang, J.-H. Han, and H. C. Park, 07.07.2021
- DFT+DMFT study of electronic correlation and structural effects in strongly correlated materials
  S. Kim, H. Park, B. Kim, H.-S. Kim, S. Y. Park, M. Kim, K. Kim, H. C. Choi, C. H. Kim, A. Go, C. J. Kang, J.-H. Han, H. C. Park, 18.06.2021
- Kick-off meeting for "ASG: Computational approaches to correlated systems: Applications to diverse materials"
  S. Kim, B. Kim, H.-S. Kim, S. Y. Park, M. Kim, K. Kim, C. H. Kim, A. Go , J.-H. Han, and H. C. Park, 21.05.2021

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 visitor-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.

Members:

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Bongjae Kim (Kunsan National University, Korea)
Hee Chul Park (PCS IBS)
Heungsik Kim (Kangwon National University, Korea)
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Choong Hyun Kim (Seoul National University, Korea)

Incommensurately stacked atomic layers
Convener: Pilkyung Moon

The weak van der Waals interaction between two-dimensional atomic layers enables various stacking geometries, such as various twist angles, without being restricted by the lattice commensuration obeyed by conventional 3D crystals. And such incommensurately stacked atomic layers provide a unique opportunity to couple the monolayer states of each layer with different wave vectors. In this project, we will explore the electronic structures and relevant physical properties such as optical selection rule, phonon, electron phase. We will put more emphasis on specific configurations which host quasicrystalline electronic states.

The aim of this Advanced Study Group provides the chance to share the novel ideas and to solve the problems through collaborations among the different approaches. We have a plan, at first, to set up the initiative problem related to the incommensurately stacked atomic layers and then to gather the branch problems through the brainstorming with all of members. There are a lot of derived phenomena by stacking 2 dimensional materials such as quasicrystal inflation pattern, multiferroic, superconductivity, and higher-order topological insulators. The grouping by overlapped topics and distinguished approaches should make synergies in collaborations. We will study the physical properties of the layered materials by topological band theory by the first principle calculation and symmetry analysis, optical transition, electron transport, field theoretical approach including interaction and disorder, and so on. Although the works are related to the theoretical interests, most of all problems will be considered by experimental realization through advice of members in experiment. We expect that the on-offline hybridised meetings offer the more active and continuous coworks.

Meetings at PCS:

- Joint meeting with ASG "Computational approaches to correlated systems: Applications to diverse materials"
  P. Moon, Y. W. Son, Y. Kim, J.-W. Rhim, N. Myoung, J.-R. Ahn, H. Yang, M. J. Park, H. C. Park, 12.07.2021 (12.07.2021 - 14.07.2021)

- Kick-off meeting of ASG "Incommensurately stacked atomic layers"
  P. Moon, Y. W. Son, Y. Kim, J.-W. Rhim, N. Myoung, J.-R. Ahn, H. Yang, M. J. Park, H. C. Park, 17.06.2021

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Nojoon Myoung (Chosun University, Korea)
Hee Chul Park (PCS IBS)
Joung-Real Ahn (SKKU, Korea)
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Young Woo Son (KIAS, Korea)

Coulomb Correlations and Coherent Spin Dynamics in Mesoscopic Weak Links
Convener: Robert Shekhter
Co-convener: Junho Suh

The interplay between two fundamental electronic degrees of freedom, charge and spin, and the quantum orbital motion of electrons in mesoscopic nanodevices will be in focus of the proposed research program of the new ASG. Three lines of theoretical and experimental research are suggested. The first line includes the effect of spin-orbit coupling (SOI) in electric weak links on the electronic transport through such systems, focusing on the possibility to generate spin currents occurring due to the SOI dynamics of electrons. Spin-induced nanomechanics (spintro-mechanics) of both the magnetic and SOI-active weak links is the subject of the study along the second research line. Coulomb promotion of spintro-mechanics and electron number parity controlled thermoelectricity phenomena are suggested as new research directions. The third research line focuses on the electromechanical performance of the superconducting weak links. Quantum fluctuations of the electronic charge, accumulated on the movable part of the weak link, caused by the non-diagonal (in terms of the electronic number) superconducting ordering, change qualitatively the nanomechanics of the device offering a quantum coherent coupling between the nanomechanical and superconducting parts of the device. Possible nanodevice applications employing the mechanical degrees of freedom of normal metals, semiconductors, magnets and superconductors will be explored in close cooperation with the experimental groups at KRISS and KIST, Korea.

Topics include:

- Single electronics
- Coulomb blockade
- Spintronics
- Nanoelectromechanics
- Spin-orbit interaction
- Magnetic exchange interaction
- Superconducting weak links
- Josephson effect

Seminars and meetings via video conference:

- Breaking Time-Reversal Symmetry and Spin Selection in chiral molecules
  Amnon Aharony, Tel Aviv University, Israel, 16.02.2021
- Nanoelectromechanical phenomena induced by Josephson force
  Leonid Gorelik, Chalmers University of Technology, Sweden, 09.02.2021
- Magnetization generated by microwave-induced Rashba interaction
  Ora Entin-Wohlman, Tel Aviv University, Israel, 12.01.2021
- Nanomechanical cat-states generated by dc-voltage driven Cooper pair box qubit
  Danko Radić, University of Zagreb, Croatia, 15.12.2020
- IBS Physics Colloquium - Spin-orbit coupling and topological geometric phases: detection by interference measurements
  Ora Entin-Wohlman, Tel Aviv University, Israel, 25.11.2020

- Clocking of single electrons via a quantum bell
  H. C. Park, R. Shekhter, C. Kim, J. Suh, 12.03.2020
- dc Shapiro steps in quantum spin Hall systems with Majorana qubit
  Sang-Jun Choi, University of Würzburg, Germany, 25.02.2020
- Nanomechanical devices as hybrid and interface devices for quantum computing
  Junho Suh, Chulki Kim, Dong Hun Lee, and Hee Chul Park, 10.12.2021
- Nanomechanics driven by superconducting proximity effect
  Robert Shekhter, Leonid Gorelik, Sergei Kulinich, Olha Baroba, and Hee Chul Park, 07.12.2021
- Electronic properties of superconducting nano-electromechanical shuttle
  Olha Barova, Anton Parafilo, Robert Shekhter, Leonid Gorelik, Sergey Kulinich, and Hee Chul Park, 30.08.2021
- Josephson energy driven nano-electromechanical system using CNT and superconducting leads
  R. Shekhter, L. Gorelik, O. M. Baroba, and H. C. Park, 22.07.2021
- Electronic properties of superconducting nano-electromechanical shuttle
  R. Shekhter, L. Gorelik, and H. C. Park, 07.07.2021
- The effect of decoherence to the evolution of the entangled cat-state
  H. C. Park, S.-J. Choi, J. Suh, 06.04.2021
- Nanomechanical cat states generated by a dc voltage-driven Cooper pair box qubit
  H. C. Park, J. Suh, R. Shekhter, 17.02.2021
- Entanglement between charge qubit states and coherent states of nanomechanical resonator generated by AC Josephson effect
  H. C. Park, O. M. Bahrova, R. Shekhter, L. Gorelik, 20.01.2021

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Deep Learning in Quantum Phase Transitions
Convener: Victor Kagalovsky

Today machine learning is perfecting its abilities and becoming the most efficient and important tool in condensed matter physics. Obtaining and representing the ground and excited states' wave functions are examples of such applications. Another application is analyzing the wave functions and determining their quantum phases.

The research of the Advanced Study Group (ASG) "Deep Learning in Quantum Phase Transitions" is planned to focus on two major applications: topological insulators and quantum strongly interacting many-body systems. Restricted Boltzmann Machines (RBM) deep learning method allows studying thermodynamics and spatial correlations of quantum phases in such systems.

Topics include:

- 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

Seminars via video conference:

- Machine learning magneto-fingerprints in mesoscopic systems
  Tomi Ohtsuki, Sophia University, Japan, 01.06.2021
- IBS Physics Colloquium - Transport evidence for a two-dimensional quantum electron solid
  Sergey Kravchenko, Northeastern University, USA, 29.04.2021
- Convolutional restricted Boltzmann machine aided Monte Carlo: An application to Ising and Kitaev models
  Ilya Eremin, University of Bochum, Germany, 20.04.2021
- Multifractality and the distribution of the Kondo temperature at the Anderson transition
  Keith Slevin, Osaka University, Japan, 15.04.2021
- Restricted Boltzmann Machines (RBM) methods for a study of novel quantum phases and quantum phase transitions in complex qubits networks
  Mikhail Fistul, RU Bochum, Germany, 09.07.2020
- Drawing phase diagrams of random quantum systems by deep learning the wave functions
  Tomi Ohtsuki, Sophia University, Japan, 07.07.2020
- Machine learning beyond the hype – principled methods for understanding physics
  David Saad, Aston University, UK, 02.07.2020
- IBS Physics Colloquium - Machine learning - potential, hype and risks
  David Saad, Aston University, UK, 30.06.2020

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Ara Go (PCS IBS)
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Keith Slevin (Osaka University, Japan)
Igor Yurkevich (Aston University, UK)

Functional Spin-Active Mesoscopic Weak Links
Convener: Robert Shekhter

Our Advanced Study Group (ASG) was active throughout the calendar year 2019, during which its activities followed the approved research plan and timeline. Collaborative efforts during three meetings on site at PCS were complemented by individual work of the ASG members during the rest of the year with regular internet contacts between members. Research carried out within the ASG has resulted in a number of papers (published, submitted or prepared for publication, refs. [1-9]). The three most significant scientific achievements, in our opinion, are the following:

1. Coulomb promoted spintromechanics [1,7,8].

We have suggested the possibility to achieve an interplay between single-electron transport phenomena caused by the Coulomb blockade of tunneling and spintromechanics in magnetic shuttle structures. 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 from a mechanically stable regime to a regime of spin-induced shuttle instabilities. 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.

2. Electromotive force generated in SOI-active weak links [2].

We have shown that microwave field irradiating the SOI-active spatially nonhomogeneous nanowire activates DC electronic transport of charge even in the absence of an external driving voltage applied. Therefore SOI-active weak link serves as a nanometer size battery with electromotive force, which can be easily measurable through detecting the microwave induced photovoltaic effect across the device.

3. Kondo tunneling through Aharonov-Casher interferometer [3].

We predict that non-trivial effect of spin-orbit interaction on many-body tunneling of electrons in the regime of a strong Coulomb blockade radically change Kondo tunneling of electrons allowing the mechanical and electric control of Kondo temperature of the device.

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

A. DC spin generation in AC driven SOI-active electric weak links [6].

In this project we have suggested that time-reversal symmetry of the SOI-active device can be broken through its irradiation by a microwave field. As a result SOI effect on electronic spin transport can be activated. A 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, was shown to inject spin-polarized electrons into the terminals. The injected spin-polarization has a DC component along the link and a rotating transverse component in the perpendicular plane. In the adiabatic, 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. We estimate the effect of spin accumulation which can be achieved in realistic SET-UP, causes by above spin-generation. Up to 10% of total electrons in a micrometer size dot can be spin-polarized by the described AC Rashba pumping mechanism.

B. Rashba spin-splitting of electrons in magnetically ordered SOI-active devices [5,9].

One of the possibilities to break time reversal symmetry of an SOI active device and therefore to activate its SOI performance is to employ materials with spin polarized electrons. Such devices can be made of magnetic materials or achieved in non-magnetic devices were spin pumping of electrons is induced by microwave radiation. In this project the particle- and spin currents between two reservoirs of spinpolarized electrons are calculated to lowest order in the tunneling through the weak link using the wide-band approximation, with emphasis on their dependence on the origin of the 'bare' magnetizations in the reservoirs. The SOI is found to generate magnetization components in each reservoir, 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 spin-polarized electrons with a non-zero component in that plane. 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 since the SOI in the weak link generates extra spin polarizations which are injected into the reservoirs.

C. Spin-geometric phase in hopping magnetoconductance [4].

In this project we theoretically identify the geometric phases of the electron spin that can be detected in measurements of charge and spin transport through Aharonov-Bohm interferometers, threaded by a magnetic flux (in units of the flux quantum), in which both the Rashba spin-orbit and Zeeman interactions are active. We show that the combined effect of these two interactions is to produce a $\sin(\Phi)$ [in addition to the usual $\cos(\Phi)$] dependence of the magnetoconductance, which amplitude is proportional to the Zeeman field. Therefore the magnetoconductance, though an even function of the magnetic field is not a periodic function of it, and a widely-used concept of phase shift in the Aharonov-Bohm oscillations, as indicated in previous work, is not applicable. We find the directions of spin-polarizations in the system, and show that in general the spin currents are not conserved, implying the generation of magnetization in the terminals attached to the interferometer.

D. Quantum Nanovibrations Entangled with Superconducting Cooper Pair Box (ongoing research).

Quantum manipulations of nanomechanical vibrations is a frontline research directions in the area of quantum communications. The possibility of qubit devices to communicate without loss of quantum coherence of the signals together with small size of the quantum devices make phonon vibrations to be a tempting component of a hybrid multi-qubit devices. To explore the possibility to use the superconducting shuttle device for quantum coherent signal transduction between Cooper pair box qubit and quantum shuttle vibrations was the motivation for the research within given project. We have shown that quantum coherent transduction of Cooper pair quantum fluctuations into quantum superposition of vibrational coherent states (implementing the quantum Schrödinger Cat state) can be achieved by DC biasing the movable Cooper pair box. It was found that at special voltage values when the mechanical frequency coincides with a frequency Josephson oscillations, the amplitude of the mechanical oscillations increases in time. As a result, the initial pure quantum state of the system (ground state) develops into one describing the entanglement of qubit state and coherent mechanical states.

E. Mechanically assisted Andreev reflection (work in progress).

Andreev reflection is a well-known phenomenon which accompanies the injection of superconducting Cooper pairs into non-superconducting metal (Andreev resistor). It is responsible for the formation of special localized at S-N interface states of a superconducting condensate which provide a supercurrent flow in SNS structures. Using nanomechanical weak links allows one to make Andreev resistor to be a functional weak link enabling to couple Cooper pairs flow to the mechanical degrees of freedom. We can call such coupling "mechanically assisted Andreev reflection". During 3-rd ASG 2019 meeting we have started a new project which aims to developing a theory of mechanically assisted Andreev reflection.

F. Experimental activity within ASG.

Experimental activity of the ASG was focused of superconducting nanomechanics. The main activity was located in both Chulki Kim and Junho Suh's groups. Experiments to observe the coherent transfer of Cooper pairs via a nanomechanical oscillator have been planned. The nanomechanical oscillator consists of a suspended SiO2 layer deposited by a layer of aluminum with probing electrodes around. One of the flexural modes of the cantilever is excited by the application of microwaves across a part of the cantilever. A Cooper-pair box is placed at the end of the cantilever in between source and drain electrodes. A gate electrode is located away to control the Coulomb energy of the Cooper-pair box. Currently, we are trying to confirm that the mechanical oscillator is actuated by the external microwaves and find a way to control its displacement accurately. We are very pleased with the fact that a number of Junho Suh's students have been involved of are planned to be involved in the ASG activity in the 2019 and its planned continuation in 2020. We see such involvement and the initiation of new projects for the students research as an important mission of the advanced study group. The list of the students, their affiliations and the projects they are involved in is presented in the attachment.

G. Exploring the "Physics of Flat Bands" as new ASG research direction.

At the initiative of Amnon Aharony, Sergej Flach presented on Nov. 18, 2019 a seminar describing the PCS activities on flat bands. Following that, our ASG met with Flach and with Alexey Andreanov on Nov. 20 to discuss possible collaborations on related topics. Possible directions included flat bands in systems with spin-orbit interactions, including possible flat bands associated with spin filtering states, the effects of disorder (especially with new distributions, e.g. percolation with two values of the random variables), and the utility of perturbations on flat bands to generate new physical properties (e.g. electrical conductivity). More discussions will be planned.

In addition to activity listed above a number of formal and informal meetings took place at the PCS IBS during three ASG meetings in year 2019. The Workshop on mesoscopic nanomechanics of which was held in connection to ASG activity was a very important opportunity to expose internationally our research. An external to ASG visitor from ICTP (Italy)- Prof. M. Kiselev was participating our activity this time working on SOI active Kondo tunneling.

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. Dominika Konikowska, her assistants Ms. Jaehee Kwon and Ms. Gileun Lee, as well as all other staff and technical support members.

Publications

1. A. D. Shkop, O. M. Bahrova, S. I. Kulinich and I. V. Krive, Interplay of Vibration and Coulomb Effects in Transport of Spin-Polarized Electrons in a Single-Molecule Transistor, submitted in Superlattices and Microstructures (2019).
2. Entin-Wohlman, R. I. Shekhter, M. Jonson, A. Aharony, Photovoltaic effect generated by spin-orbit interactions, arXiv: 1911.01168 (2019).
3. A. V. Parafilo, L. Y. Gorelik, M. N. Kiselev, H. C. Park, R. I. Shekhter, Kondo effect in Aharonov-Casher interferometer, arXiv: 1909.04524 (2019).
4. A. Aharony, O. Entin-Wohlman, Spin geometric-phases in hopping magnetoconductance and spin currents, arxiv: 1908.05869 (2019).
5. A. Aharony, O. Entin-Wohlman, R. I. Shekhter, and M. Jonson, Effects of different lead magnetizations on the Datta-Das spin field-effect transistor, The J. Phys. Chem. C 123, 11094 (2019).
6. M. Jonson, R. I. Shekhter, O. Entin-Wohlman, A. Aharony, H. C. Park, and D. Radic,

DC spin current generated by AC-driven Rashba weak links, Phys. Rev. B 100 115406 (2019).
7. Olya A. Ilinskaya, A. D. Shkop, Danko Radic, Hee Chul Park, Ilya V. Krive, Robert I. Shekhter, and Mats Jonson, Coulomb Effects on Thermally Induced Shuttling of Spinpolarized Electrons, Low Temp. Phys., 45, 1208 (2019).
8. O. A. Ilinskaya, D. Radic, I. V. Krive, R. I. Shekhter, M. Jonson, and H. C. Park, Coulomb promoted spintromechanics in magnetic shuttle devices, Phys. Rev. B, 100, 045408 (2019).
9. A. Aharony, O. Entin-Wohlaman, M. Jonson, and R. I. Shekhter, Electric and magnetic gating of Rashba-active weak links, Phys. Rev. B 97 (22), 220404(R) (2018).

List of new projects initiated by ASG activity

1. Coulomb promoted spintromechanics
2. DC spin generation in AC driven SOI-active electric weak links
3. Electromotive force generated in SOI-active weak links
4. Kondo tunneling through Aharonov-Casher interferometer
5. Rashba spin-splitting of electrons in magnetically ordered SOI-active devices
6. Spin-geometric phase in hopping magnetoconductance
7. Quantum Nanovibrations Entangled with Superconducting Cooper Pair Box
8. Mechanically assisted Andreev reflection

List of members

- *Formal members*:
  Robert Shekhter (Gothenburg University, Sweden)
  Mats Jonson (Gothenburg University, Sweden)
  Ilya Krive (Institute for Low Temperature Physics and Engineering, Ukraine)
  Amnon Aharony (Tel Aviv University & Ben Gurion University, Israel)
  Ora Entin-Wohlman (Tel Aviv University Ben Gurion University, Israel)
  Danko Radic (University of Zagreb, Croatia)
  Loenid Gorelik (Chalmers University, Sweden)
  Chulki Kim (KIST, Korea)
  Junho Suh (KRISS, Korea)
  Hee Chul Park (PCS IBS)

- *Associate members*:
  Anton Parafilo (PCS IBS)
  Mikhail Fistul (PCS IBS)
  Mikhail Kiselev (ICTP, Italy)
  Olya Ilinskaya (ILTPE, Ukraine)
  Minjin Kim (KRISS, Korea)
  Jihwan Kim (KRISS, Korea)
  Sang-Jun Choi (PCS IBS)
  Nojoon Myoung (Chosun University, Korea)
  Sejoong Kim (UST, Korea)
  Kunwoo Kim (PCS IBS)
  Donggeun Lee (KIST, Korea)

List of students supervised by ASG members:

1. Olha M. Bahrova (Interplay of Coulomb and Exchange Driving Forces in a Magnetic Shuttle Device) supervised by Prof. Ilya V. Krive (B. Verkin ILTPE, NAS of Ukraine,

Ukraine)
2. Minjin Kim (Nanomechanical characterization of quantum interference in a topological insulator nanowire) supervised by Dr. Junho Suh (KRISS)
3. Kingshuk Sarkar (Effects of Different Lead Magnetizations on the Datta–Das Spin Field-Effect Transistor) supervised by Amnon Aharony (Tel Aviv University)
4. Barbara Keran Supervised by Danko Radic (University of Zagreb)
5. Hokyun Lim (Coulomb blockade in double shuttles) supervised by Chulki Kim (KIST)
6. Minsol Son (Quantum transport and Machine Learning in double quantum dots) supervised by Nojoon Myoung (CU)
7. In-Gu Jung (Quantum Hall and Coulomb blockade) supervised by Hyungkook Choi (JBNU)

3.1.6 Lectures, Colloquia, Symposia and Seminars at the Center

Date	Title	Speaker
16.12.2021	Hybrid Exact Diagonalization and Density Matrix Renormalization Group Approach to the Thermodynamics of Low-Dimensional Interacting Quantum Systems	S. K. Saha, India
07.12.2021	Mean-field approach for skyrmion lattices in frustrated antiferromagnets	O. Utesov, Russia
02.12.2021	Nonlinear speed-ups in ultracold quantum gases	S. Deffner, USA
01.12.2021	Non-Equilibrium Properties of Open Quantum Systems	I. Vakulchyk, PCS IBS
30.11.2021	Flat bands and topological polarization	T. T. Heikkilä, Finland
26.11.2021	Rank-2 Toric code	Y.-T. Oh, Korea
26.11.2021	Hybridization of the 3D Toric code and the X-cube model	J. Kim, Korea
24.11.2021	Electric field induced flat bands in frustrated quantum spin models	V. Ohanyan, Armenia
23.11.2021	What is quantum complexity?	A. Hamma, USA
17.11.2021	Frustrated spin-1/2 lattice models at three-colorable point and flat-band physics	O. Derzhko, Ukraine
16.11.2021	Quantum geometry effects on superconductivity, interacting Bose-Einstein condensate, and light-matter interactions in flat bands	P. Törmä, Finland
11.11.2021	Quantum control to probe non-equilibrium dynamics	S. Campbell, Ireland
11.11.2021	Holography Complexity and Thermodynamic Volume	R. Mann, Canada
09.11.2021	Dynamic thermalization and chaos in many-spin systems	B. Fine, Russia

04.11.2021	Many-body finite-time quantum machines	V. Mukherjee, India
02.11.2021	Quantum transport enabled by vibrations and non-adiabatic transitions	S. Wuester, India
28.10.2021	Searches for Axions at the University of Western Australia	M. Tobar, Australia
19.10.2021	MBL-mobile: Many-body-localized engine	N. Y. Halpern, USA
14.10.2021	Identifying Correlation Clusters in Many-Body Localized Systems	K. Hémery, Germany
12.10.2021	Flatbands as an arena for designing superconducting and topological systems	H. Aoki, Japan
07.10.2021	Acoustic transport and superconducting fluctuations in 2D materials	K. Sonowal, PCS IBS
05.10.2021	Quantum fluctuations in nonlinear Schrödinger breathers	O. Marchukov, Germany
16.09.2021	Probing many-body mobility-edge and proximity effect with tensor networks	M. Serbyn, Austria
14.09.2021	Nonequilibrium entropy and the second law in quantum many-body systems	P. Strasberg, Spain
09.09.2021	Constructing large period discrete time crystals with quantum repetition codes	R. Bomantara, Australia
19.08.2021	Flat bands, sharp physics	D. Leykam, Singapore
12.08.2021	Multipoint correlation functions: spectral representation and numerical evaluation	S.-S. B. Lee, Germany
10.08.2021	Operator growth dynamics in the integrable and non-integrable Ising spin chain	J. D. Noh, Korea
03.08.2021	Quantum local random networks and the statistical robustness of quantum scars	F. Surace, Italy
27.07.2021	Classical simulation of quantum devices	A. Purkayastha, Ireland
22.07.2021	Quantitative study of the Fock space localization in the Sachdev-Ye-Kitaev model	M. Tezuka, Japan
20.07.2021	Operator complexity: the long story	R. Shir, Israel
15.07.2021	Toward to reliable AI for scientific computing	H. Yoon, Korea
15.07.2021	Interferometry with Bose-Einstein condensates	E. M. Rasel, Germany
13.07.2021	Prethermalization and thermalization in isolated quantum systems	M. Rigol, USA
06.07.2021	Non-reciprocal phase transitions	R. Hanai, Korea
06.07.2021	Toward a Spin Jam Theory, Semi-classical and Quantum	S.-H. Lee, USA
01.07.2021	Dissipative Quantum Dynamics – From Order to Chaos	P. Ribeiro, Portugal

29.06.2021	Frustrated quantum magnetism: The flat-band scenario	J. Richter, Germany
24.06.2021	Hilbert space shattering	R. Nandkishore, USA
22.06.2021	From dynamics to statistical physics: Chaotic route to thermalization	D. He, China
21.06.2021	Signatures of topological edge states in spin-spin correlations	S. Verma, India
17.06.2021	Magic configurations in Moiré Superlattice of Bilayer Photonic crystal: Almost-perfect flat-band and Unconventional Localization	H. S. Nguyen, France
15.06.2021	Entanglement transitions	R. Vasseur, USA
10.06.2021	Disorder-Free Localization in an Interacting 2D Lattice Gauge Theory	P. Karpov, Germany
10.06.2021	Novel transport phenomena in topological semimetals at high magnetic fields	G. Bednik, USA
08.06.2021	Emergent Symmetry and Quantum Information Scrambling in Brownian SYK model	S. Xu, USA
04.06.2021	Equilibrium and Non-equilibrium Gross–Pitaevskii Lattice Dynamics: Interactions, Disorder, and Thermalization	Y. Kati, PCS IBS
01.06.2021	Machine learning magneto-fingerprints in mesoscopic systems	T. Ohtsuki, Japan
27.05.2021	Fock-space correlations and many-body localisation	D. Logan, UK
26.05.2021	Frustration-induced Athermal Behaviors: Hilbert Space Fragmentation and Quantum Many-Body Scars	K. Lee, USA
18.05.2021	Perfect flat band and trimerized charge ordering out of strong spin-orbit interaction	C. Hotta, Japan
13.05.2021	Macroscopically degenerate zero energy states in quasicrystalline bilayer systems	B.-J. Yang, Korea
04.05.2021	Hidden dualities in 1D quasiperiodic lattice models	M. Gonçalves, Portugal
29.04.2021	Transport evidence for a two-dimensional quantum electron solid	S. Kravchenko, USA
27.04.2021	Valley pseudospin-selective light–exciton interaction in multilayered WS	S.-H. Gong, Korea
20.04.2021	Convolutional restricted Boltzmann machine aided Monte Carlo: An application to Ising and Kitaev models	I. Eremin, Germany
15.04.2021	Multifractality and the distribution of the Kondo temperature at the Anderson transition	K. Slevin, Japan

13.04.2021	Disorder and correlations in flat-band systems: A platform for the Sachdev-Ye-Kitaev model	T. Sedrakyan, USA
08.04.2021	Summary of research on dynamics of weakly nonintegrable systems using unitary maps	M. Malishava, PCS IBS
07.04.2021	Instantaneous thermalization in dilute gas phase of SYK model	S. N. Singh, India
06.04.2021	Dynamical aspect of flat-band many-body localization	Y. Kuno, Japan
30.03.2021	Localization properties in disordered 2- and 3-dimensional Lieb lattices and their extensions	R. Roemer, UK
24.03.2021	Quantum master equation approach to transport	J.-S. Wang, Singapore
11.03.2021	Designer quantum states in atomic lattices and van der Waals heterostructures	P. Liljeroth, Finland
09.03.2021	Physics of incommensurately stacked two-dimensional atomic layers - from moiré superlattices to quasicrystals	P. Moon, China & USA
04.03.2021	Interplay of flat electronic bands with Holstein phonons	C. Feng, USA
02.03.2021	Localized dynamics following a quantum quench in a non-integrable system: an example on the sawtooth ladder	S. Choudhury, USA
25.02.2021	Dynamical control of phases and time crystal in an atom-photon system	J. Cosme, Philippines
23.02.2021	Interplay of disorder and interactions in a flat-band supporting diamond chain	A. Sharma, India
19.02.2021	A lunar orbit array for ultralong wavelength observation	X. Chen, China
18.02.2021	Hybridization mechanism of the dual proximity effect in superconductor-topological insulator interfaces	N. Sedlmayr, Poland
16.02.2021	Breaking Time-Reversal Symmetry and Spin Selection in chiral molecules	A. Aharony, Israel
09.02.2021	Nanoelectromechanical phenomena induced by Josephson force	L. Gorelik, Sweden
04.02.2021	From dual-unitary to quantum Bernoulli circuits: entangling power's role in constructing a quantum ergodic hierarchy	A. Lakshminarayan, India
02.02.2021	From Local to Latent Symmetries and Hidden Degeneracies in Wave Mechanical Systems	P. Schmelcher, Germany
28.01.2021	Prethermal phases of matter: time-crystals, time quasi-crystals, and beyond	W. W. Ho, USA

26.01.2021	Local Symmetries in Wave Mechanics: From Fundamentals to First Applications	P. Schmelcher, Germany
21.01.2021	OTOC, quantum chaos and the correspondence principle	G. Benenti, Italy
19.01.2021	PT Symmetry	C. M. Bender, USA
12.01.2021	Magnetization generated by microwave-induced Rashba interaction	O. Entin-Wohlman, Israel
07.01.2021	Ergodic and non-ergodic many-body dynamics in strongly nonlinear lattices	R. Dubertrand, UK
22.12.2020	Sachdev-Ye-Kitaev Physics	Y. Jia, USA
15.12.2020	Nanomechanical cat-states generated by dc-voltage driven Cooper pair box qubit	D. Radić, Croatia
10.12.2020	Non-Hermitian degeneracies of Optical modes in Non-integrable dielectric Microdisks	C. Yi, Korea
08.12.2020	Valley Hall effect caused by the drag effect in two-dimensional crystals	L. Golub, Russia
01.12.2020	Information theoretical method for understanding complex systems	E.-j. Kim, UK
25.11.2020	Spin-orbit coupling and topological geometric phases: detection by interference measurements	O. Entin-Wohlman, Israel
19.11.2020	Axion Quasiparticles for Axion Dark Matter Detection	D. Marsh, Germany
17.11.2020	Speed limits and time-information uncertainty relations	A. del Campo, Spain
10.11.2020	Exploring collective states of superconducting qubits	A. Ustinov, Germany
03.11.2020	Accelerating Axion Search at CAPP in Korea	W. Chung, Korea
29.10.2020	Coherence effect in a multi-level quantum-dot heat engine	J. Um, Korea
27.10.2020	Beyond the standard quantum limit of parametric amplification	F. Deppe, Germany
20.10.2020	The European experimental landscape of direct detection of Axion Dark Matter	C. Gatti, Italy
13.10.2020	Thermodynamic uncertainty relation in quantum transport: Theory and Experiment	B. K. Agarwalla, India
08.10.2020	Quantum algorithms for computational science	D. Park, Korea
06.10.2020	Quantum distance and anomalous Landau levels of flat bands	J.-W. Rhim, Korea
25.09.2020	When Ms. Topology meets Mr. Bath	J. Han, PCS IBS

22.09.2020	Application of catastrophe theory in the quantum mechanics	M. Cosic, Serbia
17.09.2020	Construction of FQH local model from Long-ranged CFT Hamiltonian	D. Nandy, Poland
15.09.2020	Harnessing currents of particles for spectroscopy in small-ring lattices with binary mixtures	L. Molina, Chile
10.09.2020	New insights from the electron-phonon interaction in the Anderson-Holstein model	B. De, India
08.09.2020	Sachdev-Ye-Kitaev superconductivity: Quantum Kuramoto and generalized Richardson models	A. Chudnovskiy, Germany
03.09.2020	Topological transition on anisotropic hexagonal lattices and effective phonon model for the quantum Hall transition	A. Sinner, Germany
01.09.2020	Topological delocalization in two-dimensional quantum walks	J. Asboth, Hungary
25.08.2020	The random quantum comb: From compact localized states to many-body scars	O. Hart, UK
20.08.2020	Observation of excess electronic recoil events in XENON1T	S. Kazama, Japan
18.08.2020	A brief introduction to quasiparticles in frustrated magnets	C. Castelnovo, UK
11.08.2020	Non-local interactions enhance the performances of quantum batteries: the case of SYK	D. Rosa, Korea
04.08.2020	An example of flat-band many body localization	Y. Kuno, Japan
28.07.2020	Complex behavior of topological defects in polariton quantum fluids	S. Koniakhin, France
21.07.2020	Partial synchronization patterns in brain networks - interplay of dynamics, delay, and network topology	E. Schöll, Germany
16.07.2020	First-principles theory of quantum defects in wide-gap semiconductors for solid-state quantum technologies	H. Seo, Korea
09.07.2020	Restricted Boltzmann Machines (RBM) methods for a study of novel quantum phases and quantum phase transitions in complex qubits networks	M. Fistul, Germany
07.07.2020	Drawing phase diagrams of random quantum systems by deep learning the wave functions	T. Ohtsuki, Japan
02.07.2020	Machine learning beyond the hype – principled methods for understanding physics	D. Saad, UK

02.07.2020	Short Introduction to Observational entropy	D. Šafránek, USA
30.06.2020	Machine learning - potential, hype and risks	D. Saad, UK
18.06.2020	Exciton-Polaritons in Artificial Lattices and Electron transport in Bose-Fermi Hybrid Systems	M. Sun, PCS IBS
16.06.2020	Spatio-temporal dynamics of magnon BEC at room temperature	S. Demokritov, Germany
09.06.2020	Stationary current of bosonic carriers across the flux rhombic lattice	A. Kolovsky, Russia
02.06.2020	Eigenstate extraction with neural-network tomography	C. Gneiting, Japan
26.05.2020	Diffusion, subdiffusion, critical point and localization in a disordered spin chain	A. Scardicchio, Italy
19.05.2020	Quantum synchronization in nanoscale heat engines	S. Vinjanampathy, India
12.05.2020	Anomalous levitation and annihilation in Floquet topological insulators	J. Asboth, Hungary
07.05.2020	Valley Hall effect caused by the phonon and photon drag	M. Glazov, Russia
28.04.2020	Strong quantum correlations of a cold atomic gas in experiment and theory	J. Brand, New Zealand
23.04.2020	Non-Hermitian surface waves in electromagnetism and beyond	D. Leykam, PCS IBS
16.04.2020	Bogolon-pair-mediated superconductivity	I. Savenko, PCS IBS
09.04.2020	The wonderful world of flat bands	S. Flach, PCS IBS
27.02.2020	Caging quantum interacting particles in dispersionless lattices	C. Danieli, Germany
26.02.2020	Topological solitons in chiral magnets	C. Heo, Belgium
25.02.2020	dc Shapiro steps in quantum spin Hall systems with Majorana qubit	S.-J. Choi, Germany
22.01.2020	Higher-order topological insulator phase in twisted bilayer graphene (2)	Y. Kim, Korea
21.01.2020	Quantum criticality near the Mott transition from a spin liquid to a Fermi liquid in two dimensions	J.-H. Han, Korea
20.01.2020	Emergence of supersymmetry from spin-lattice coupling: Lattice vibration as a knob for novel quantum criticality	S. Han, Korea
16.01.2020	Higher-order topological insulator phase in twisted bilayer graphene	Y. Kim, Korea
09.01.2020	First-principles studies on ultrafast carrier dynamics in materials	J. Bang, Korea

06.01.2020	A renormalization group approach with dimensional regularization to the scaling properties of the Ising nematic quantum criticality	K.-M. Kim, Korea
12.12.2019	Computational material designs: current challenges and future directions	C.-J. Kang, USA
03.12.2019	Stochastic work extraction in active particles heat engines	R. Marathe, India
02.12.2019	Non-Hermitian systems and perspective	S. Modak, India
22.11.2019	Flatband generators	W. Maimaiti, PCS IBS
19.11.2019	Is there a Floquet Lindbladian?	A. Schnell, Germany
15.11.2019	The Gravity and Quantum Matters	S.-J. Sin, Korea
14.11.2019	Many-body invariants for topological insulators: multipole, Chern, and hinge states	B. Kang, Korea
05.11.2019	Unusual magnetotransport in EuMnBi2 due to the interplay between spin-orbit coupling and magnetic structure	K.-M. Kim, Korea
24.10.2019	Stochastic thermodynamics of glassy systems	H. Rahbari, Korea
22.10.2019	Advances in non-Hermitian and topological photonics	A. Cerjan, USA
11.10.2019	Noncoplanar multi-k states in frustrated magnets	M. Zhitomirsky, France
10.10.2019	Bifurcations of dividing surfaces in chemical reactions	P. Salas, Spain
08.10.2019	The low-density expansions for the homogeneous dipolar Bose gas	A. Cherny, Russia
01.10.2019	Chaotic compound states in electronic, photonic, atomic and nuclear processes	V. Flambaum, Australia
30.09.2019	Effects of Dark Matter in atomic and nuclear phenomena	V. Flambaum, Australia
17.09.2019	First order superconducting quantum phase transition in the deformed Sachdev-Ye-Kitaev (SYK) model	A. Chudnovskiy, Germany
05.09.2019	Visualized wave mechanics by coupled macroscopic pendulums	M. Kiselev, Italy
03.09.2019	Measurement-driven single temperature engine	P. Talkner, Germany
13.08.2019	Dirac cones and mass terms in bosonic spectra	S. Kumar, India
25.07.2019	Ensembles of random generators of Markovian quantum evolution: spectral properties and universality	S. Denisov, Norway

23.07.2019	Finite-size scaling and the multi-crossover critical behaviour in a 2D incompressible flocking model	W. Qi, China
18.07.2019	An Atom as an Onion	Y.-K. Kim, USA
11.07.2019	How to observe and quantify quantum-discorded states in solid-state setups	I. Yurkevich, UK
09.07.2019	Superconducting edge states in topological insulators	V. Kagalovsky, Israel
04.07.2019	Chasing Neutrinos Around the World: A Personal History	M. Vagins, USA
02.07.2019	Phases and phase transitions of Bose condensed light	A. Kuklov, USA
27.06.2019	Two-level systems in quasi 2D photon gas	V. Fleurov, Israel
25.06.2019	Quantum heat machines with trapped ions	S. Chand, India
18.06.2019	Nano-electronics using quantum circuits as artificial atoms on a chip	F. Nori, Japan & USA
10.06.2019	First M87 Event Horizon Telescope Results - The Shadow of the Supermassive Black Hole	B. W. Sohn, Korea
04.06.2019	Topological order, higher-form symmetry, and dense quark matter	Y. Hirono, Korea
21.05.2019	Quantum gases in disorder	G. Shlyapnikov, France
14.05.2019	Dynamical localization and delocalization in Floquet systems	T. Cadez, China
09.05.2019	Flatbands in twisted Dirac materials	J. Jung, Korea
08.05.2019	Topological phases characterized by the Stiefel-Whitney number in carbon allotropes	Y. Kim, Korea
23.04.2019	Non-Hermitian photonics based on quantum-inspired symmetries	L. Ge, USA
23.04.2019	Novel manifestations of topological states of matter: From Floquet topological states to the search of topological states in non-Hermitian lattices	L. Foà Torres, Chile
22.04.2019	Quantum billiards, graphene billiards and neutrino billiards	B. Dietz, China
16.04.2019	How to decompose a graph into a tree-like structure	S.-i. Oum, Korea
11.04.2019	Transport properties of the Discrete Nonlinear Schrödinger Equation	S. Iubini, Italy
09.04.2019	Localization and slow-relaxation phenomena in the Discrete Nonlinear Schrödinger Equation	S. Iubini, Italy

04.04.2019	Thermodynamics of negative-temperature states	S. Iubini, Italy
02.04.2019	Reflecting on an alternative (parity-time-symmetric) quantum theory, and its analog in optics	R.-K. Lee, Taiwan
26.03.2019	Controlling self-similar waves and rogue waves in nonlinear optical and atomic waveguides	S. Thokala, India
21.03.2019	Tidal deformability of neutron stars and gravitational waves	C.-H. Lee, Korea
14.03.2019	Analytic continuation via domain knowledge free machine learning	H. K. Yoon, Korea
12.03.2019	Maximum quantum entropy method: The analytic continuation of matrix-valued Green's functions	J.-H. Sim, Korea
26.02.2019	Apical ion dynamics-modulated in-plane transport properties in cuprates	S. Kim, Korea
21.02.2019	Cooling electrons in nanoelectronic devices	Y. Pashkin, UK
20.02.2019	Resilience of Majorana fermions in the boundary of 1D topological superconductor in presence of disorder	A. Habibi, Iran
19.02.2019	Quantum correlations in optomechanical crystals	F. Bemani, Iran
13.02.2019	Anomalous heat transport in the one-dimensional classical systems	A. Kundu, India
12.02.2019	Correlations in dynamics and localization of two interacting particles in lattices	T. Chattaraj, Canada
11.02.2019	JUNO: a 20-kton multi-purpose underground observatory	J. Cao, China
07.02.2019	Collective machines	J. Thingna, PCS IBS
22.01.2019	Controllable dissipators for quantum electric circuits	M. Möttönen, Finland
16.01.2019	Engineering topological states of polaritons with non-Hermitian potentials	M. Fraser, Japan
10.01.2019	The new results of neutrino oscillations from the T2K experiment	T. Nakaya, Japan
09.01.2019	Time-domain approach to ultrafast quantum optics	A. Moskalenko, Germany
07.01.2019	Many-body invariance of multipoles in higher-order topological insulators	B. Kang, Korea

3.1.7 Long-term Visitor Reports

Novel quantum spin states such as the low temperature quantum state
Seung-Hun Lee: June 28 – July 16, 2021

Motivation of my visit to PCS-IBS

When magnetic moments in the microscopic world are interacting with each other in a situation resembling that of complex love triangles, frustration arises and may lead to seemingly 'erratic' states. Those 'erratic' states, categorized as spin liquid and spin glass, are usually highly susceptible to external perturbations. In particular, those glassy magnets exhibit peculiar time-dependent response in bulk magnetization, which is called aging and memory effect. My group has been studying these effects in several magnetic glassy materials, and shown that a scaling of magnetic memories with time can be used to classify magnetic glassy materials into two distinct classes; spin glass and spin jam.

My visit to PCS-IBS was to discuss with theorists including Alexei Andreanov about how to understand theoretically the physics of spin jam.

Activities at PCS-IBS

I had discussion almost every day with Alexei Andreanov. In addition, I had taken following activities during my stay at PCS-IBS.

1. On June 25, to initiate discussion to find out possible collaboration with theorists in Daejeon, I had a zoom meeting with three theorists, Se Kwon Kim, Sungbin Lee, Eun-Gook Moon, at the Korea Advanced Institute of Science and Technology (KAIST).

2. On June 28, I visited and gave a seminar at KAIST, titled 'Toward a spin jam theory, semi-classical and quantum', and had follow-up discussion with Professor Sungbin Lee.

3. On July 5, I had a zoom meeting with Alexei Andreanov of PCS-IBS and Sungbin Lee of KAIST.

4. On July 6, at 2am I had a zoom meeting with Gia-Wei Chern of University of Virginia (UVA) to find out a possibility of collaboration between UVA theorists and PCS theorists.

5. On July 6, I gave a seminar at PCS-IBS, titled 'Toward a spin jam theory, semi-classical and quantum'.

6. On July 9, Alexei and I had a zoom meeting with Gia-Wei Chern and Israel Klich of University of Virginia for discussion.

7. On July 12, Alexei and I had a zoom meeting with Gia-Wei Chern and Israel Klich of University of Virginia for discussion.

8. On July 14, I gave an informal talk and led discussion for the Advanced Study Group at PCS-IBS.

9. On July 15, Alexei and I had a zoom meeting with Israel Klich of University of Virginia for discussion.

Scientific issues discussed

1. Is spin freezing a salient feature expected of typical spin liquid candidates?

2. What is the nature of the frozen state? Can it be categorized as spin jam?
3. Can we come up with a theoretical framework to understand the physics of spin freezing of spin liquids and the nature of the frozen state?

Future works to do

1. We (Alexei, Gia-Wei, Israel, and myself) identified what to do to address the scientific issues mentioned above. And divided our works; Gia-Wei will focus on Monte Carlo simulations, Alex and Israel will focus on constructing a possible phenomenological framework, while I will focus on experimental work.
2. In addition to short papers that we may be able to write, we will try to write a review paper together on glassy states of densely populated magnets.

Conclusion of my visit

My visit was very constructive. By doing thorough literature search and discussions, we were able to identify important scientific issues in the field, and identify what to do to understand the physics of freezing phenomena that are so common in spin liquid candidates. This visit firmly established the collaboration between PCS-IBS and University of Virginia.

Saturation dynamics in PT symmetric optical structures
Sinan Gündoğdu : April 8 – June 30, 2019

This report summarize the progress done in the project between April-June 2019. The aim of the project is to explore the PT-symmetric non-Hermitian systems defined by Maxwell-Bloch equation. Many work done on non-Hermitian optics in the literature involves class A laser model which do not include gain saturation, while there are increasing interest in class B regime, since electrically pumped semiconductor lasers are in this regime. For this reason, we started by analysis of steady states of the system. The steady state with zero frequency exhibits Hopf bifurcations. We calculated the steady state inversion, and carried a linear stability analysis on it and observed that just above the threshold, instabilities start. Then we expanded our analysis to plane wave and obtain the electric field, which have bistable solutions, and obtained an expression for instability onset.

1. Lorentz-Haken system

Due to its analogy with the Maxwell-Bloch equations and notational simplicity, we started to analysis of the Lorentz-Haken system, which is analogous to. We obtained the so-called second laser threshold which shows, again the onset of the instability in lasers. However for the second threshold to exist, the time constants of the laser, photon lifetime, gain recovery time and dephasing time should be within a specific region, which is called the bad cavity conditions (BCC). Within this region, above the second threshold periodic pulsations and chaotic pulsations were observed numerically. The instability threshold is as low as 8 times the lasing threshold. However, this regime falls into a very specific part of the class C lasers.

To understand the role of topology on the initial dynamics of these lasers, we made an eigenvalue analysis of the system linearized around the $E = 0$ state. To observe the effect of the coupling, We started the simplest case, the dimer, and defined with each element having independent pumping rate. We observed that both the coupling constant and the detuning play a very strong role in the initial dynamics. In the low coupling regime, lasing just above the threshold starts with zero frequency, and as the coupling increases, initial lasing oscillation frequency increases proportionally. However, exceptional points of the system is below the lasing threshold, which means, initial dynamics does not exhibit a topological phase transition.

2. Lorentz-Haken dimer

To realize the most basic non-Hermitian system on these, we analyzed the time dynamics of the Lorentz-Haken dimer. To do this, we used a 4th order Runge-Kutta method. We started the calculation from the zero-frequency steady state initial conditions. After waiting for the transient effects to diminish, we calculated the Fourier transform of the electric field. In the calculated spectrum as a function of the pumping rate at different coupling rates and pump differences, all spectra starts with zero frequency, just above the threshold (pump rate = 1). Since these spectra was calculated for BCC time constants, When two components of the dimer is equally pumped $dr = 1$, with the increased coupling rate, we observed the instability starts at even lower pump rates. However, once the unequal pumping is introduced, the instability threshold increases drastically. Experimentally, this enables one to manage instabilities just by adding one extra electrode to the system. Due to the simplicity it has important implications in laser science. Another thing we observed is that at higher pump differences, as opposed to pulsations we observed singlefrequency modulation of the optical spectra, which is also technologically interesting.

3. Next-nearest-neighbour coupled topological insulator laser

In parallel to the above work, we started on a numerical study of a lattice defined in the tight-binding framework with interaction terms defined with both the nearest and the nextnearest neighbour (NNN) coupling. The total Hamiltonian is given by;

$$H = \sum_{x,y} \left(H_a + H_b + H_{ab} + H_{ab}^{\ddagger} \right) \tag{1}$$

where

$$\begin{aligned} H_a &= \hat{a}_{x,y}^{\ddagger} \left(\left(2J \cot \frac{\phi}{2} + M \right) \hat{a}_{x,y} + J \csc \frac{\phi}{2} \sum_{\pm} \hat{a}_{x,y\pm 1} \right) & (2) \\ H_b &= \hat{b}_{x,y}^{\ddagger} \left(\left(2J \cot \frac{\phi}{2} - M \right) \hat{b}_{x,y} + J \csc \frac{\phi}{2} \sum_{\pm} \hat{a}_{x\pm 1,y} \right) & (3) \\ H_{ab} &= J e^{i\phi/4} \csc \frac{\phi}{2} \times \left(\hat{a}_{x,y}^{\ddagger} \left(\hat{b}_{x,y}^{\ddagger} + \hat{b}_{x\pm 1,y\pm 1}^{\ddagger} \right) \right) & (4) \end{aligned}$$

This structure is similar to the Haldane model, and existence of the edge modes depend on the detuning parameter, M (1). Therefore, it enables switching of the edge-mode propagation by controlling the detuning.

Two sites with independent detuning was shown with blue and green dots. Lines between the curves describe Hermitian couplings. The Hamiltonian above describes the linear system and does not include gain saturation. Although in this case, which corresponds to class A laser system, edge modes was successfully observed, it is known that once the nonlinearities are includes, system is non necessarily stable. Therefore, it is interesting to realize the model using class B laser equations, which also describe the carrier densities. We are particularly interested if the NNN coupling is stable for class B model compared to nearest-neighbour coupling only.

4. Conclusion

One of the most important outcome of this work has been the demonstration of stabilization of chaos in class-C laser model using non-Hermitian coupling. We will also test the stability in the case of RNGH instability. we also started to study the class B equations in NNN-coupled lattice, with motivation of stabilization of edge modes in topological insulator lasers.

Non-Gibbs states on a Bose-Hubbard lattice
Alexander Cherny : September 18 – December 10, 2019

Scientific activities

1. On 8th of October, I gave the talk "The low-density expansions for the homogeneous dipolar Bose gas"

Abstract of the talk:

The properties of the two-body scattering with zero relative momentum for the dipole-dipole interaction are considered. The low-density expansions for the energy, chemical potential, and condensate depletion of the homogeneous dipolar Bose gas are obtained. We discuss how these results can be derived within the Bogoliubov approach from the assumption of universality of the lowdensity expansions. The long-range asymptotics of the normal and anomalous two-point correlation functions are obtained analytically for the dilute dipolar Bose gas.

2. The paper "The low-density expansions for the homogeneous dipolar Bose gas at zero temperature" by Alexander Yu. Cherny [arXiv: 1910.05489 (2019)] has been written and submitted to Phys. Rev. A.

In this work, we obtained the expansions of energy, chemical potential, and condensate depletion at small densities:

$$\varepsilon = \frac{2\pi\hbar^2}{m}an\left[1-\epsilon_{dd}+\frac{128}{15\sqrt{\pi}}\sqrt{na^3}\mathcal{Q}_5(\epsilon_{dd})\right], \tag{1}$$

$$\mu = \frac{4\pi\hbar^2}{m}an\left[1-\epsilon_{dd}+\frac{32}{3\sqrt{\pi}}\sqrt{na^3}\mathcal{Q}_5(\epsilon_{dd})\right], \tag{2}$$

$$\frac{n-n_0}{n} = \frac{8}{3\sqrt{\pi}}\sqrt{na^3}\mathcal{Q}_3(\epsilon_{dd}). \tag{3}$$

Here we use the notation

$$\mathcal{Q}_n(y) = (1-y)^{n/2}{}_2F_1\left(\frac{1}{2},-\frac{n}{2};\frac{3}{2};-\frac{3y}{1-y}\right) \tag{4}$$

with ${}_2F_1$ being the hypergeometric function. The parameter $\epsilon_{dd} = r_{dd}/a$ is the dipolar ratio with a and $r_{dd} = d^2m/(3\hbar^2)$ being the scattering length and the effective dipolar range, respectively.

The long-range dipole-dipole potential is regularized with the appropriate regularization, which leads to the jump of the effective scattering amplitude at zero momentum. This procedure allows us to obtain the leading term $4\pi/3d^2n$ in the expansion of the chemical potential. This term has a simple physical interpretation: it is the classical energy of a dipole in the local electric or magnetic field created by distant dipoles encircling the dipole. The term gives the thermodynamic instability at $\epsilon_{dd} = 1$, which is exactly the same value of the ratio when the Bogoliubov spectrum becomes complex (the dynamic instability). However, the Lee-Huang-Yang correction can stabilize the system for $\epsilon_{dd} > 1$ at the price of breaking the translation invariance and forming droplets. When $n_{cr} < n \ll 1/a^3$ the dipolar gas can be stable, where the critical density is given by

$$n_{cr} = \frac{\pi(\epsilon_{dd}-1)^2}{1728a^3\left[1+\frac{5}{4}(\epsilon_{dd}-1)\right]^2}. \tag{5}$$

The asymptotics of the normal and anomalous correlators and the pair distribution function are calculated analytically:

$$
\begin{aligned}
\frac{\langle\hat{\psi}^\dagger(\mathbf{r})\hat{\psi}(0)\rangle}{n} &\backsimeq 1+\frac{1}{2r^2}\sqrt{\frac{an}{\pi^3}}f(\epsilon_{dd},\theta), &(6)\\
\frac{\langle\hat{\psi}(\mathbf{r})\hat{\psi}(0)\rangle}{n} &\backsimeq 1-\frac{1}{2r^2}\sqrt{\frac{an}{\pi^3}}f(\epsilon_{dd},\theta), &(7)\\
g(\mathbf{r}) &= 1-\frac{1}{r^4}\frac{1}{4\pi^{5/2}n^{3/2}a^{1/2}}h(\epsilon_{dd},), &(8)
\end{aligned}
$$

where the anisotropic factors are given by

$$
\begin{aligned}
f(\epsilon_{dd},\theta) &= \sqrt{1+2\epsilon_{dd}}\left(1+\frac{u}{2}\ln\frac{1-u}{1+u}\right), &(9)\\
u &= \cos\theta\sqrt{\frac{3\epsilon_{dd}}{1+2\epsilon_{dd}}},\quad \cos\theta=(\mathbf{e}_d\cdot\mathbf{e}_r), &(10)\\
h(\epsilon_{dd},\theta) &= \sqrt{1+2\epsilon_{dd}}\frac{1+7\epsilon_{dd}+10\epsilon_{dd}^2-3\epsilon_{dd}(\epsilon_{dd}+5)\cos\theta^2}{[1+\epsilon_{dd}(2-3\cos\theta^2]^3}. &(11)
\end{aligned}
$$

As the dipolar forces get larger, the decaying parts of the correlators strongly depend on the angle between the dipoles and the relative distance. When ϵ_{dd} exceeds some critical value, the decaying part changes sign with increasing the angle. The pair distribution function, which gives the probability to find a particle near another particle, is located within the very narrow cones near $\theta=0$ and $\theta=\pi$ in the vicinity of ϵ_{dd}. This means that the dipolar gas should have some tendency to form filaments along the dipole direction when the dipolar ratio is close to one.

We discuss the nature of the divergence arising in the calculation of the energy within the Bogoliubov theory with the effective potential. It is shown how to use the universality of the expansions to avoid the divergence. As a byproduct, we consider the two-body scattering problem with zero relative momentum for the dipole-dipole interaction and derive the asymptotics of the wave function

$$
\varphi(\mathbf{r})=1-\frac{a}{r}+\frac{r_{dd}}{r}P_2(\mathbf{e}_d\cdot\mathbf{e}_r)+\cdots \tag{12}
$$

and the correction to the scattering length of the hard-sphere potential with the radius a_{sp}

$$
a=a_{sp}-\frac{3}{25}\left(2\frac{a_{sp}^2}{r_0^2}-7\frac{a_{sp}}{r_0}+8\right). \tag{13}
$$

for small values of the dipolar range. Here r_0 is the cutoff parameter of the dipole-dipole potential.

The suggested regularization of the dipolar interactions gives quite a consistent picture. Nevertheless, it is worth comparing the results of this paper with Monte-Carlo simulations, which have not been done yet for a homogeneous dipolar gas to the best of the author knowledge. The obtained density expansion for the ground-state energy can be useful for constructing the local density approximation.

3. The system of classical nonlinear oscillators in the random field for nonzero temperature was considered within the project with Kati Yagmur, Sergej Flach, and Mikhail Fistul about the problem of localization on the GP lattice. This is an extension of the previous result for the ground state energy.

The model of noninteracting classical oscillators is the GP lattice with disorder and zero hopping terms. Then the Hamiltonian is given by

$$H = \sum_{l=1}^{M} \epsilon_l n_l + \frac{U}{2} n_l^2 \tag{14}$$

with random on-site energies ϵ_i, obeying the probability density distribution

$$\rho(\epsilon) = \frac{1}{2W} \times \begin{cases} 1, & \text{for } -W \leqslant \epsilon \leqslant W, \\ 0, & \text{elsewhere.} \end{cases} \tag{15}$$

It follows from this equation that the average value $\bar{\epsilon} = \lim_{M\to\infty} M^{-1}\Sigma_i \epsilon_i = \int d\epsilon \rho(\epsilon) = 0$, while the variance σ_ϵ is finite. The "occupation numbers" are related to the classical fields by the equation $n_l = \psi_l^* \psi_l$. The total number of particles $N = \Sigma_l n_l$ and the energy $E = H$ are conserved during the evolution. Further, all quantities with the dimension of energy are given in units of U. For example, the energy, inverse temperature, and border W of the distribution (15) are rescaled as $E \to E/U$, $\beta \to \beta U$, and $W \to W/U$.

At zero temperature, the energy per site $\varepsilon = E/M$ is given by

$$\varepsilon = \begin{cases} \frac{4}{3} n^{3/2} \sqrt{W} - nW, & \text{for } \quad 0 \leqslant n \leqslant W, \\ \frac{n^2}{2} - \frac{W^2}{6}, & \text{for } \quad n \geqslant W. \end{cases} \tag{16}$$

The equilibrium properties of the model for arbitrary positive temperature can easily be derived within the grand canonical Gibbs ensemble. The Gibbs thermodynamic potential $\Omega = E - TS - \mu N = \omega M$ is calculated as

$$\omega(\beta, \mu) = -\frac{1}{\beta} \frac{1}{M} \sum_{l=1}^{M} \ln z_l, \tag{17}$$

$$z_l = \int_0^{+\infty} \mathrm{d}n_l \exp\left(-\beta \left[(\epsilon_l - \mu) n_l + \frac{1}{2} n_l^2\right]\right) = f\left(\frac{\sqrt{\beta}(\epsilon_l - \mu)}{\sqrt{2}}\right) \frac{1}{\sqrt{2\beta}}, \tag{18}$$

where by definition $f(x) = e^{x^2} \mathrm{erfc}(x) \sqrt{x}$ with the error function $\mathrm{erfc}(x) = 1 - \frac{2}{\sqrt{x}} \int_0^x \mathrm{d}t e^{-t^2}$. The sum in Eq. (17) can be reduced to the integral with the distribution function (15), because $\frac{1}{M} \sum_l g(\epsilon_l) = \int \mathrm{d}\epsilon \rho(\epsilon) g(\epsilon)$ for any function $g(x)$ in the thermodynamic limit. Then the grand canonical potential per site is given by

$$\omega(\beta, \mu) = \frac{\mu^2}{2} + \frac{W^2}{6} + \frac{1}{2\beta} \ln\left(\frac{2\beta}{\pi}\right) - \frac{1}{\sqrt{2} W \beta^{3/2}} \int_{x_1}^{x_2} \mathrm{d}x \ln \mathrm{erfc}(x) \tag{19}$$

with the integral limits

$$x_1 = -(W + \mu)\sqrt{\frac{\beta}{2}}, \quad x_2 = (W - \mu)\sqrt{\frac{\beta}{2}}. \tag{20}$$

The density of particles and total energy per site can be derived from the grand Gibbs potential (19) and the relations $n = -\left(\frac{\partial \omega}{\partial \mu}\right)_\beta$ and $\epsilon = \left(\frac{\partial(\beta\omega)}{\partial \beta}\right)_\alpha$ (here $\alpha = -\beta\mu$)

$$n = \mu - \frac{1}{2W\beta} [\ln \mathrm{erfc}(x_2) - \ln \mathrm{erfc}(x_1)], \tag{21}$$

$$\varepsilon = \frac{\mu^2}{2} - \frac{W^2}{6} + \frac{1}{2\beta} + \frac{1}{(2\beta)^{(3/2)}W} \int_{x_1}^{x_2} \mathrm{d}x \ln \mathrm{erfc}(x) + \frac{1}{(2\beta)^{(3/2)}W} [x_1 \ln \mathrm{erfc}(x_2) - x_2 \ln \mathrm{erfc}(x_1)]. \tag{22}$$

The energy as a function of the density at given temperature can be drawn as a parametric plot with the chemical potential as the parameter. The influence of disorder is negligible at the temperatures of order of $W \sim 1/\beta$.

4. The infinite temperature line was studied in the Bose-Hubbard model with a harmonic trap.

We consider the Hamiltonian

$$\hat{H} = \sum_{i \neq j} J(i-j) \hat{a}_i^\dagger \hat{a}_i + \sum_i \varepsilon_i \hat{a}_i^\dagger \hat{a}_i + \frac{U}{2} \hat{n}_i (\hat{n}_i - 1) \tag{23}$$

with the isotropic harmonic potential $\varepsilon = k^2 i^2$, where $i = (i_1, \ldots, i_d)$ is a multi-index in general, d is the lattice dimension. The total number of bosons is equal to N, and the number of lattice sites are *not* fixed. The parameter $1/k^d$ is the analogue of the volume for a trapped system. Then the thermodynamic limit is $k^d N = \mathrm{const}$, and $N \to \infty$. This limit actually allows us to replace the sum over lattice sites by the correspondent integral

$$\sum_i f(\varepsilon_i) \simeq \int \mathrm{d}\varepsilon \frac{\Omega(d)}{2k^d} \varepsilon^{\frac{d-2}{2}} f(\varepsilon), \tag{24}$$

where $\Omega(d) = 2\frac{\pi^{d/2}}{\Gamma(d/2)}$ is the surface of unit sphere in d dimensions, $\Gamma(x)$ is the Gamma-function.

By analogy with the paper, we suppose that the chemical potential is negative and tends to infinity when $\beta \to 0$. This means that the quantity $\alpha = -\mu\beta$ is positive and much more than β in this limit. Then one can neglect the hopping and interaction terms in the partition function of the grand canonical ensemble. So, the density matrix in zero-order approximation is given by

$$\hat{\rho}_0 = \frac{\exp\left[-\Sigma_i (\varepsilon_i \beta + \alpha)\hat{n}_i\right]}{Z_0}. \tag{25}$$

$$Z_0 = \mathrm{Tr} \exp\left[-\sum_i (\varepsilon_i \beta + \alpha)\hat{n}_i\right] \tag{26}$$

The partition function is easily calculated

$$Z_0 = \prod_i z_i, \quad z_i = \frac{1}{1 - e^{-\varepsilon_i \beta - \alpha}}. \tag{27}$$

With Eq. (24) we obtain in the thermodynamic limit in the particular case $d = 2$

$$\ln Z_0 = \sum_i \ln z_i = \frac{\pi}{k^2} \int_0^\infty \mathrm{d}\varepsilon \ln[1 - z e^{-\varepsilon\beta}] = -\frac{\pi}{k^2\beta} \mathrm{Li}_2(z), \tag{28}$$

where $z = e^{-\alpha}$ is the fugacity and $\mathrm{Li}_n(z)$ is the polylogarithm.

We obtain that the particle and energy "densities" in two dimensions are given by

$$n = k^2 N = -\frac{\pi}{\beta} \ln(1-z), \tag{29}$$

$$\varepsilon_{ext} = k^2 E_{ext} = \frac{\pi}{\beta^2} \mathrm{Li}_2(z), \tag{30}$$

$$\varepsilon_{int} = k^2 E_{int} = U\frac{\pi}{\beta}\left[\frac{z}{1-z} + \ln(1-z)\right], \tag{31}$$

where the external and interaction energies are defined as $E_{ext} = \langle \Sigma_i \varepsilon_i \hat{n}_i \rangle$ and $E_{int} = \left\langle \Sigma_i \frac{U}{2} \hat{n}_i(\hat{n}_i - 1)\right\rangle$, while the average of the hopping terms amounts to zero.

Excluding the fugacity from Eqs. (29)-(31), we obtain that

$$\varepsilon = \varepsilon_{int} + \varepsilon_{ext} \simeq \varepsilon_{ext} \simeq \frac{n}{\beta} \tag{32}$$

in the leading order. We come to the conclusion that the *infinite temperature line does not exist in the $\varepsilon - n$ plane*, because it goes to infinity when $\beta \to 0$.

For the *classical GP lattice, the partition function diverges for any finite temperature*, as one can see by straightforward calculations. The nature of this divergence can be understood from the expression for the average occupation number in the quantum BH model:

$$n_i = \langle \hat{n}_i \rangle = \frac{1}{e^{\varepsilon_i \beta + \alpha} - 1}. \tag{33}$$

It *cannot* be reduced to the classical limit $\frac{1}{\varepsilon_i \beta + \alpha}$ (as was done in the homogeneous case) for any values of the model parameters, because $\alpha \simeq -\ln[\beta n/\pi] \to \infty$ in the limit of infinite temperatures.

Accumulated recording in quantum systems
Peter Talkner : September 2 – October 5, 2019

1. Preamble

On the following pages the main scientific results of my stay at PCS IBS from 2019, September 2 till October 5 are presented. These results have been obtained in a close and very fruitful collaboration with Dr. Juzar Thingna. For a series of four lectures I gave on "Thermodynamics of Small System" I refer to the notes which are available from Dr. Thingna's web page.

2. Introduction

Measurement plays an important role in science in general and in quantum mechanics in particular. While in classical systems measurements can in principle be performed with unlimited precision and without any influence on the measured object, for quantum systems often there are principle limits of the achievable precision and unavoidable, sometimes drastic back-actions on the state of the measured object. The frequent repetition of the same measurement may either lead to the total freezing of the system's dynamics, known as Zeno effect or to a steady heating of the system, effects that are alien to classical systems. Because the only way of gaining information about he state of a quantum system is by measuring, understanding the measurement process and its impact on the considered system is vital. From the point of view of a theoretician, projective measurements, wherein the system state collapses to the measured state, are most common. This idea of projective measurements leads to simplistic theoretical approaches but lacks information about the measuring device and its properties as well as about possible deviations from the ideal picture.

Alternatively, as shown in this work, one could adapt von Neumann's projective measurement approach to generalized measurements in which the measuring device is a quantum object that comes in contact with the system. During contact both system and the device affect each other and hence by projectively measuring the device after contact one can infer information about the system. In this report we explore the possibility of repeated contacts of the measuring device to record information from the system which would be read out at the very end. We compare our N contacts single measurement (SM) approach to the N contacts N measurements (MM: multiple measurements) case where after each contact the measuring device is read out.

3. Generalized Measurements

Following von Neumann's approach we consider a quantum measuring device called "pointer" that comes in contact with the system for a short time τ_p with strength g. The contact time is extremely short as compared to the timescale of system dynamics, such that, during the contact the system does not evolve. Thus whenever the pointer connects to the system the density matrix of the combined system pointer is modified as

$$\tilde{\varrho}_{tot}(t) = V_t \rho_{tot}(t) V_t^\dagger \tag{1}$$

with $\rho_{tot}(t)$ being the density matrix at the time immediately before the contact, t, evolved from the initial time $t_0 = 0$ at which the total density matrix factorizes in a system part ρ and the initial pointer state σ, $\rho_{tot}(0) = \rho \otimes \sigma$. The pointer does not evolve in time as long as it is not in contact with the system. Thus the time evolution of the total system for a contact-free episode is given by $\rho_{tot}(t) = U_t \rho \otimes \sigma U_t^\dagger$ with U_t being the solution of the system Schrödinger equation,

$$i \frac{\partial U_t}{\partial t} = H U_t. \tag{2}$$

Above $U_0 = \mathbb{I}$, $\hbar = 1$ (throughout), and H is the system Hamiltonian. During the short time τ_p the contact is governed by the Hamiltonian $H_I = \lambda M P$, where λ is the coupling parameter, M the observable to be measured and P the momentum operator conjugate to the position X of the pointer. This leads to an information transfer between the system and the pointer according to the unitary operator

$$V = e^{-i\kappa M P}, \tag{3}$$

where $\kappa = g\tau_p$ and M is the measured system operator.

The above described procedure could be repeated for $N+1$ contacts and a final projective measurement is performed to read the pointer state. For the sake of simplicity the time T between subsequent contacts is assumed to be always the same Thus, after a series of $N+1$ contacts between system and measurement apparatus, the non-normalized reduced system density matrix, conditioned on the outcome x, is given by an operation ϕ_x, i.e. by a completely positive linear map acting on the initial system density matrix ρ. It is given by

$$\phi_x[\rho] = \mathrm{Tr}_P[Q_x (VU)^N V \rho \otimes \sigma V^\dagger (U^\dagger V^\dagger)^N], \tag{4}$$

where $U := exp[-iHT]$ denotes the time evolution operator of the system governing the system's dynamics between subsequent contacts with the measuring apparatus. Above the first interaction V between system and measurement apparatus acts on the initial state. The trace Tr_P is taken over the pointer space. The probability density function (pdf) $P_{SM}(x)$ of finding x is given by

$$P_{SM}(x) = \mathrm{Tr}_S[\phi_x[\rho]] \tag{5}$$

For the sake of simplicity, both the system Hamiltonian H and the measured system operator M are supposed to have a pure point spectrum without degeneracy. Hence, they can be represented as

$$H = \sum_p e_p |p\rangle\langle p| \tag{6}$$

$$M = \sum_m \mu_m |m\rangle\langle m|. \tag{7}$$

where $\{|\rangle\}$ and $\{|m\rangle\}$ are two orthonormal eigenbasis sets of H and M, respectively. Further, e_p and μ_m are the respective eigenvalues. Because in general the Hamiltonian H and the operator M do not commute, the overlap between arbitrary elements of the two basis sets can be different from zero, $\langle p|m\rangle \neq 0$.

Using these spectral representations and the positionrepresentation of the pointer density matrix

$$\sigma(x-a, x-b) = \langle x|e^{-iaP}\sigma e^{ibP}|x\rangle, \tag{8}$$

we obtain

$$\begin{aligned}
\phi_x[\rho] &= \sum_{\vec{m},\vec{m}'} D_\rho^{\vec{m},\vec{m}'} \sigma(x - S_{\vec{m}}, x - S_{\vec{m}'})|m_N\rangle\langle m_N'|, \qquad (9)\\
S_{\vec{m}} &= \kappa \sum_{j=0}^{N} \mu_{m_j},\\
D_\rho^{\vec{m},\vec{m}'} &= \langle m_0|\rho|m_0'\rangle \sum_{\vec{p},\vec{p}'} C_{\vec{p},\vec{p}'}^{\vec{m},\vec{m}'} \exp\left[-i\sum_{j=1}^{N}(e_{p_j} - e_{p_j'})\right],\\
C_{\vec{p},\vec{p}'}^{\vec{m},\vec{m}'} &= \prod_{j=1}^{N} \langle m_j|p_j)(p_j|m_{j-1}\rangle\langle m_{j-1}'|p_j')(p_j'|m_j'\rangle.
\end{aligned}$$

While the sets related to the indices m_i and m_i', $\vec{m}^{(\prime)} = \{m_0^{(\prime)}, \ldots, m_N^{(\prime)}\}$ contain $N+1$ elements, those related to the indices p_i and $p_i^{(\prime)}$, $\vec{p}^{(\prime)} = \{p_1^{(\prime)}, \ldots, p_N^{(\prime)}\}$ consist of N elements. With Eq. (5) the probability distribution function (pdf) of observing the pointer in the measured state x becomes

$$P_{SM}(x) = \sum_{\vec{m},\vec{m}'} D^{\vec{m},\vec{m}'} \sigma(x - S_{\vec{m}}, x - S_{\vec{m}'})\delta_{m_N,m_N'}. \tag{10}$$

with the coefficient $D^{\vec{m},\vec{m}'}$ as described below Eq. (9).

The transfer of the information on the observable M of $N+1$ contacts into the same pointer state yields to shifts of the x and y arguments of the pointer state density matrix by $S_{\vec{m}}$ and $S_{\vec{m}'}$. Instead, following the MM procedure, one may store the result of each contact as obtained by a projective measurement on a pointer state in $N+1$ pointers. The operation $\phi_{\vec{x}}$ yielding the nonnormalized system density matrix conditional on the sequence $\vec{x} = \{x_0, x_1, \ldots, x_N\}$ results as

$$\begin{aligned}
\phi_{\vec{x}}[\rho] &= \phi_{x_N}^T\left[\phi_{x_{N-1}}^T\left[\ldots\phi_{x_0}^0[\rho]\right]\right], \qquad (11)\\
\phi_x^0 &= \mathrm{Tr}_P[Q_x V\rho V^\dagger], \qquad (12)\\
\phi_x^T &= \mathrm{Tr}_P[Q_x VU\rho U^\dagger V^\dagger],
\end{aligned}$$

describing $N+1$ measurements of the same observable M at equal intervals of duration T.

$$\begin{aligned}
\phi_{\vec{x}}[\rho] &= \sum_{\vec{m},\vec{m}'} D_\rho^{\vec{m},\vec{m}'} \Sigma_{\vec{x}}^{\vec{m},\vec{m}'} |m_N\rangle\langle m_N'|, \qquad (13)\\
\Sigma_{\vec{x}}^{\vec{m},\vec{m}'} &= \prod_{j=0}^{N} \sigma(x_j - \kappa\mu_{m_j}, x_j - \kappa\mu_{m_j'}),
\end{aligned}$$

where the coefficients $D_\rho^{\vec{m},\vec{m}'}$ are defined as below Eq. (9). Analogously to Eq. (5), the probability $P_{MM}(\vec{x})$ to find the sequence of measurement results $\vec{x}$ is determined by

$$P_{MM}(\vec{x}) = \mathrm{Tr}_S \phi_{\vec{x}}(\rho). \tag{14}$$

This yields for the probability $P_{MM}(x)$ to find the for the sum x of the individual outcomes of measurement the expression

$$P_{MM}(x) = \int d^{N+1}x P_{MM}(\vec{x})\delta(x - \sum_{j=0}^{N} x_j) = \sum_{\vec{m},\vec{m}'} D_\rho^{\vec{m},\vec{m}'} Q^{\vec{m},\vec{m}'}(x)\delta_{\vec{m_0},\vec{m_0}'}, \tag{15}$$

where the integral extends over all possible $N+1$ measurement outcomes. Further

$$Q^{\vec{m},\vec{m}'}(x) = \int d^{N+1}x\delta(x - \sum_{j=0}^{N} x_j)\Sigma_{\vec{x}}^{\vec{m},\vec{m}'}. \tag{16}$$

In the expressions above the initial pointer state was not specified. We assume that this initial state in position representation is a pure Gaussian state,

$$\begin{aligned} \sigma &= \sigma(x,y)|x\rangle\langle y| \\ \sigma(x,y) &= \frac{1}{\sqrt{2\pi\langle X^2\rangle}} \exp\left[-\frac{x^2+y^2}{4\langle X^2\rangle}\right] \end{aligned} \tag{17}$$

Where $\langle X^2\rangle$ is the variance of the pointer and quantifies the standard deviation of the measuring device. We now may compare probability distributions of x for the N-fold contact and the N-fold measurement scenarios. In the first case, described by Eq. (10), due to its σ-dependence, the distribution displays Gaussian peaks at $x = (S_{\vec{m}} + S_{\vec{m}'})/2$. Under the assumption that the scaled variance $\langle X^2\rangle/\kappa^2$ of the pointer is much smaller than the smallest distance of the eigenvalues of the measured observable M, all peaks with $S_{\vec{m}} \neq S_{\vec{m}'}$ are suppressed by an exponential factor $e^{-(S_{\vec{m}}-S_{\vec{m}'})^2/(8\langle X^2\rangle)}$. Then only those peaks at values corresponding to sums of $N+1$ eigenvalues of the observable M contribute to the distribution. The width of these peaks are given by the pointer state variance $\langle X^2\rangle$ and hence are independent of the number of measurements. The weight of the peaks is determined by sums over the complicated coefficients $D^{\vec{m},\vec{m}'}$ and in general can only be determined numerically.

In the case of $N+1$ Gaussian measurements the integration over the intermediate measurement results can be performed to yield

$$Q^{\vec{m},\vec{m}'}(x) = \sigma_{N+1}(x - S_{\vec{m}}, x - S_{\vec{m}'}) \exp\left[-\frac{\kappa^2\Sigma_{l,j=0}^{N}\left(\mu_{m_j} - \mu_{m_j'} - \mu_{m_l} + \mu_{m_l'}\right)^2}{16\langle X^2\rangle(N+1)}\right] \tag{18}$$

where

$$\sigma_N(x,y) = \frac{1}{2\pi\langle X^2\rangle N} \exp\left[-\frac{x^2+y^2}{4\langle X^2\rangle N}\right] \tag{19}$$

With increasing number of measurements, the contributions of the Gaussians at $x = (S_{\vec{m}} + S_{\vec{m}'})/2$ increase in width and decrease in height such that they merge into a broad distribution for large enough N.

This qualitative comparison already clearly indicates the main difference between the SM and the MM approaches. While in the first case the probability distribution of the finally measured pointer position allows one to resolve different realizations of the sums of $N+1$ eigenvalues, for the sum of individually measured eigenvalues the distribution soon looses any detailed structure merging to a broad curve with little structure even for not too large values of N .

Based on this work we would further like to utilize the N contact single measurement approach as a diagnostic tool to assess the functioning of a quantum Otto engine. If a cycle of such an engine is performed within a finite time, coherences may be build up. With projective diagnostic energy measurements any coherences are eliminated. Whether this influences the performance of the engine in a negative way presents an open question.

Symmetry breaking in generalizations of SYK model
Alexander Chudnovskiy: August 29 – October 3, 2019

During my stay at IBS PCS from August 29 till October 3 2019, I performed investigations on phase transitions in systems with quenched random interactions. My research focused on several interconnected problems described below.

1. Phase transition in random XY model

In close collaboration with Prof. Dr. A. Andreanov, I investigated the phase transition from disordered to the ordered phase in the random XY-model. The random XY-model is formulated as a direct generalisation of the well-known Sherrington-Kirkpatrick (SK) model of Ising spin-glass to the XY-spins. The Hamiltonian of the model is formulated as

$$H=\sum_{i,j=1}^{N} J_{ij}(S_i^x S_j^x + S_i^y S_j^y), \tag{1}$$

where the couplings are random gaussian distributed quantities with zero mean and variation given by

$$\langle J_{ij} J_{i'j'}\rangle = \frac{J^2}{N}\delta_{ii'}\delta_{jj'}. \tag{2}$$

Despite the superficial similarity to the SK model, little is know about the phase diagram of the XY model. The crucial difference between the two models arises due to quantum fluctuations in the XY model. Those fluctuations, absent in the SK model, generally tend to destroy the spin-ordering, ultimately leading to the quantum disordered ground state, that shows no order parameter, and strong time decay of spin correlations. This ground state is usually called quantum paramagnet. Previous results on quantum spin systems mostly concern the transverse field Ising models, in which the quantum fluctuations are introduced by (random or non-random) transverse field acting on each spin, $H=\sum_{i=1}^{N} h_i S_i^x$. The transverse field induces quantum fluctuations due to the noncommutativity of $\hat{S}^z$ and $\hat{S}^x$ operators. It is known, that increase to the transverse field leads to the quantum phase transition from the spin-ordered (for example the spin glass) phase to the quantum disordered phase.

The situation is much more involved in the XY model because of its different symmetry. The XY model possess the symmetry (the rotation of spins in the XY plane), which provides for strong quantum fluctuations. However, in the symmetric case, it still remains unclear whether the quantum fluctuations can prevent the ordering of spins at zero temperature. At the same time, the presence of symmetry, which would be spontaneously broken in the ordered phase, puts the XY spin model in the class of superconducting phase transitions. This feature makes the investigations of the phase diagram of the random XY model highly relevant for the physics of high-T_c superconductors, and other strongly correlated electron systems.

Besides the formulation in terms of spin operators, the XY Hamiltonian can be equivalently formulated in terms of hard core bosons, where the rising and lowering spin operators are associated with the boson creation and annihilation operators $(\hat{b}^{+}, \hat{b})$ respectively. In such formulation, the ordered phase is associated with the Bose condensation, in which nonzero averages of creation and annihilation operators such as $\langle \hat{b} \rangle \neq 0$ appear.

Together with Dr. Andreanov, we investigated yet another formulation of the XY model, where the rising and lowering spin operators are determined as composite two-fermion operators, corresponding physically to creation and annihilation of local spin-singlets – the local preformed Cooper pairs: $\hat{S}^{-} = c_{\downarrow} c_{\uparrow}$, $\hat{S}^{+} = c^{+}_{\downarrow} c^{+}_{\uparrow}$. In this formulation, the Hamiltonian of random XY model describes random hopping of Cooper pairs. The Hamiltonian of the model for the hopping of local singlets reads

$$H_s = \frac{1}{4} \sum_{i,j=1} N J^s_{ij} (c^{+}_{i\uparrow} c^{+}_{i\downarrow} c_{j\downarrow} c_{j\uparrow} + c^{+}_{j\uparrow} c^{+}_{j\downarrow} c_{i\downarrow} c_{i\uparrow}), \tag{3}$$

where the couplings are again gaussian distributed as in the initial version of the XY model, Eqs. (1) and (2). The existence of preformed local Cooper pairs naturally poses the question about their phase coherence, which would mark the onset of true off-diagonal long-range order. At the same time, the randomness of interactions suggests, that, if present, the ordered phase may have glassy features. In that case the phase of the wave function does not fluctuate in time, but has different values at different sites i.

In order to investigate the existence of the off-diagonal long-range order, together with Dr. A. Andreanov I developed mean field treatment of the model Eq, (3). In frame of that treatment, we introduced anomalous fields that correspond to the following averages

$$f^{\tau\tau'}_i = -\langle c^{\tau}_{i\downarrow} c^{\tau'}_{i\uparrow} \rangle, \quad \bar{f}^{\tau\tau'}_i = -\langle \bar{c}^{\tau}_{i\uparrow} \bar{c}^{\tau'}_{i\downarrow} \rangle. \tag{4}$$

The time-nonlocal structure of the fields in Eq. (4) implies, that if the fields $f(\tau - \tau')$, $\bar{f}(\tau - \tau')$ acquire nonzero expectation values, then there is a phase coherence between the spin-up and spin-down electrons, which goes beyond the time-local singlets present in the initial Hamiltonian (3). Together with the fields $f^{\tau\tau'}_i$, $\bar{f}^{\tau\tau'}_i$, we introduced complementary dual fields $\bar{\xi}^{\tau\tau'}_i$, $\xi^{\tau\tau'}_i$, which play the role of self energy parts in the anomalous Greens functions, and derived the mean field equations for the four introduced fields. In order to obtain a solution of the mean field equations, we assumed, that the time dependence of the anomalous fields $f(\tau - \tau')$, $\bar{f}(\tau - \tau')$, as well as the corresponding self energy parts $\bar{\xi}_i(\tau - \tau')$, $\xi_i(\tau - \tau')$, is sharply peaked at $\tau - \tau' = 0$, and it decays with time on the time-scale $1/(\alpha J_s)$, where α is a dimensionless parameter controlling the decay time scale, and the coupling constant J_s provides the overall energy scale in the model. The mean field treatment culminated in the equation for the anomalous self-energy, which is analogous to the gap equation in the conventional superconductivity. The gap equation can be represented the following dimensionless form

$$1 = C \frac{\zeta^{2/3}}{\alpha^{2/3}} \theta \sum_{\nu_n} \frac{\varphi(\nu_n)^2}{\nu_n^2 + \zeta^2 \varphi(\nu_n)^2},$$

where ζ denotes the dimensionless self-energy part, $\zeta = \xi/(\alpha J_s)$, $\theta = T/(\alpha J_s)$ denotes the dimensionless temperature. $\varphi(\nu_n)$ is a dimensionless function of the Matsubara frequency $\nu_n = \pi\theta(2n + 1)$, obtained as Fourier transform of the sharply peaked function $\varphi(\tau - \tau')$ that determines the time-dependence of the anomalous fields. Solution of the saddle point equations for different temperatures indicates a first order phase transition from the normal to the superconducting state. As one crosses the phase transition temperature, the anomalous self-energy, as well as the off-diagonal correlation functions $f(\tau - \tau')$, $\bar{f}(\tau - \tau')$ exhibit a finite jump from zero to a finite value. The difference of free energies in the superconducting and in the normal state shows a structure with two minima, one at zero and one at a finite value of the superconducting order parameter, which is characteristic for the first order phase transition.

Therefore, in coarse of our investigations we discovered a first order phase transition from the normal to the superconducting phase in a model with random hopping of singlet pairs. The transition is characterised by the appearance of anomalous correlation functions with a finite correlation time. In continuation of this investigation, we will analyse thermodynamic and transport properties of the discovered superconducting phase. Furthermore, taking into account the equivalence of the model with random hopping of preformed singlets and the random XY-spin model, a question of interpretation of the found phase transition in terms of the random XY-model naturally arises. We worked on this problem together with Dr. A. Andreanov very intensively during the last week of my visit. This collaboration will be continued. In particular, the possibility of the replicasymmetry breaking in the ordered phase of the random XY-model will stay in focus of our further collaboration with Dr. A. Andreanov.

2. Quantum phase diagram and possible superconductivity in SYK (Sachdev-Ye-Kitaev) model.

Being invented as solid state theory related to a holographic dual to gravity theories, the Sachdev-Ye-Kitaev model proved to be a promising starting point for understanding strongly correlated systems. In particular, it was shown recently, that SYK model can reproduce properties of so-called strange (or incoherent) metals – the metallic state which is present in many strongly correlated electron systems. At the same time, being formulated for spinless electrons, SYK model does not exhibit superconductivity. My investigations conveyed during the stay in IBS PCS focused on the search of a minimal modification (or deformation) of the SYK model that would induce the superconducting phase. I found, that inclusion of spin in the SYK model and an extension of the SYK Hamiltonian with a term describing the random hopping of preformed singlet pairs does lead to the sought for superconducting ground state. The Hamiltonian of the extended SYK model reads

$$H = \frac{1}{4} \sum_{i,j,k,l=1}^{N} J_{ijkl} c^+_{i\uparrow} c^+_{j\downarrow} c_{k\downarrow} c_{l\uparrow} + H_s. \tag{5}$$

Here the first term is the Hamiltonian of the SYK model generalised on fermions with spin, and the second term represents random hopping of preformed local singlets, as given by Eq. (3). The couplings J_{ijkl} are random gaussian distributed with zero mean and variation given by $\langle J_{ijkl} J_{i'j'k'l'} \rangle = J^2/(2N^3)\delta_{il'}\delta_{jk'}\delta_{kj'}\delta_{li'}$. I performed the mean field analysis of the phase diagram resulting from the Hamiltonian (5) using technical approach similar to the one described in more detail in the previous section. I came to the conclusion, that the SYK term in the Hamiltonian generally tends to suppress the superconductivity. However, this tendency can be overcome by strong enough hopping of the preformed Cooper pairs, which is described by the Hamiltonian H_s. The main result of this part of my investigations is summarised by the quantum phase diagram of the extended SYK model Eq. (5).

Therefore, I found a minimal extension of the SYK model that possesses a superconducting ground state for a wide range of parameters. This model demonstrates a fist order quantum phase transition from the superconducting to the incoherent SYK phase, The spectral properties of the superconducting phase are close to the properties of a gapless superconductor, in particular the quasiparticle spectrum exhibits a soft-gap behaviour with incoherent quasiparticles.

3. Non-equilibrium quasi-stable superconductor state in SYK model.

The mean-field analysis of the SYK model shows, that despite the pure SYK model does not have the superconducting ground state, there is a solution of the mean field equations with superconducting order. This solution corresponds to a local minimum of free energy, which has however a higher energy than the normal state. It follows, that the superconducting state can be a quasi-stable non-equilibrium state of the SYK model.

Together with Dr. A. Andreanov, we posed the following problem: what should be the nonequilibrium conditions that put the SYK system in the superconducting state? After that question is resolved, it is naturally to investigate the relaxation time from the metastable superconducting state to the normal ground state. As a first step of this research, I performed a formulation of the SYK model in frame of the Keldysh formalism, which is an appropriate tool for analytical investigation of non-equilibrium strongly interacting systems. I derived the quantum kinetic equation for the fermion distribution function. The solution of that equation and search for the initial non-equilibrium distribution function that puts the system in the superconducting state is in progress. It will be accomplished in a prolongation of our cooperation with Dr. A. Andreanov after the end of my visit to IBS PCS.

During my visit I benefited from intensive scientific exchange with members of the ASG "Functional Spin-Active Mesoscopic Weak Links“ and members and visitors of IBS PCS: R. Shekhter, I. Krive, M. Kiselev, M. Fistul, A. Cherny. In scientific conversations with Dr. A. Cherny we revealed an interesting open problem of the existence of dimer phase in diluted dipolar quantum gases. This problem seems to be amenable to the treatment by extended Skornyakov-Ter Martirosyan method, which I used for description of quantum phases in diluted spinor quantum gases. Together with A. Cherny, we plan future collaboration on that problem.

Superconducting corrections to valley acoustoelectric effect in 2D materials
Kabyashree Sonowal: July 14 – September 21, 2019

Carried out a research project whose details are as follows (July 14 – August 15):

I have started working on a project with team leader Ivan Savenko, and collaborator Vadim Kovalev. The aim of this project is to study the acoustoelectric effect in Transition metal dichalcogenide (TMD) monolayers, resulting from its interaction with Rayleigh surface acoustic waves (SAW). The starting point, was a thorough reading of the recent PRL paper, Valley acoustoelectric effect. In this paper, the TMD layer is placed on a piezoelectric substrate, and a Bleustein-Gulyaev(BG) SAW wave travels along its surface. The interaction between them is via piezoelectric mechanisms, and this gives rise to an acoustoelectric current comprising of three contributions: conventional diffusive current, valley dependent current due to trigonal warping, and the third one is the valley hall current due to Berry phase. The theory introduced in this paper, opens up a lot of scope to works related to manipulation of valley transport by acoustic methods.

As an extension of this work, in this project, we plan to study the same effect in a setup where the TMD layer is placed on an isotropic substrate (instead of piezoelectric) and a Rayleigh Surface wave(instead of BG) propagates on the surface. Rayleigh Surface waves, are elastic waves which cause displacement of the substrate medium, which in turn results in finite strain. So, the difference is, now the source of perturbation is a deformation potential arising from the strain caused due to the propagation of Rayleigh waves. Strain, is known to induce pseudomagnetic fields in 2D crystals. These fields are known to produce interesting effects like the formation of Landau levels in graphene, and this has been experimentally verified too. These pseudomagnetic fields can also be exploited to engineer time-reversal invariant topological phases in TMDs.

So, in this project, it will be interesting to see how the strain induced pseudomagnetic fields modify the acoustoelectric current and how its resulting consequences can be further used to study other interesting physical phenomena.

As of now, I have done some calculations to analyse the interaction of electrons in a deformation potential, and using these results, now I am calculating the current using Boltzman transport theory. There is a force due to the interaction potential resulting out of the strain produced by the Rayleigh SAW waves, and this creates electron density fluctuations in the conduction band. Due to these electron density fluctuations, we get an acoustoelectric current. We will then analyse the nature of this current and its physical implications.

Carried out a research project whose details are as follows (August 16 – September 21):

I continued working on the project on acoustoelectric effect in Transition metal dichalcogenides(TMDCs), that results from its interaction with Rayleigh surface acoustic waves, with team leader Ivan Savenko and collaborator Vadim Kovalev.

We take MoS2, as an example of Transition metal dichalcogenide, and take it as the material in this particular project. To understand the nature of interaction in any material, caused due to the propagation of Rayleigh waves, I read the paper 'Rayleigh surface wave interaction with 2D exciton Bose-Einstein Condensate', which describes the formalism for interaction of Rayleigh surface Acoustic wave (SAW) travelling on a semiconductor substrate with the excitonic gas in a quantum well located on the substrate surface. From this paper, I worked out the analytical framework to describe a Rayleigh SAW wave travelling on the surface of an isotropic substrate. I derived the complete expression for substrate displacement vectors, due to a Rayleigh wave, by solving the wave equation satisfied by them. The amplitude coefficients were also computed for this particular problem, in terms of intensity. These displacement vectors are required to arrive at the strain.

The formulation for strain was taken from the PRL paper, 'Quantum Spin Hall Effect in two dimensional crystals of Transition metal dichalcogenides'. In this paper, the authors present a proposal for engineering the Quantum Spin Hall effect in strained 2D crystals and heterostructures made using TMDCs. This paper, and the references therein, are good sources to know about interesting effects that arise when materials are under the effect of perturbation due to pseudomagnetic fields resulting from strain. We expect to see such effects in this project too.

From this paper, I understood the formalism to introduce the effect of strain on the band structure and use it for this project in case of MoS2. I learnt to write the perturbation Hamiltonian for strain induced interaction. I then derived the rank two strain tensor using the displacement vectors for displaced surface of the isotropic substrate due to the propagation of Rayleigh SAW waves. The strain Hamiltonian, comprises of components of this strain tensor.

The total Hamiltonian is then the addition of the material Hamiltonian for TMDC(a two band Hamiltonian in continuum limit), and the strain Hamiltonian. Using an unitary transformation learnt by referring to the paper 'Valley transport of photon- dressed quasiparticles in two-dimensional Dirac semiconductors', I analytically calculated the interaction potential energy experienced by the MoS2 electrons in the presence of strain. The gradient of this interaction energy gives the force that causes the electron density fluctuations in TMDCs, resulting in the acoustoelectric current. I am now, performing calculations explicitly, to get the drift and the diffusive current using Boltzman transport theory. After getting the expressions for these two current contributions, I plan to calculate the current that also includes trigonal warping contribution and Valley Hall effect contribution.

Talks,seminars and discussions:

1. I have attended four seminars on Monday 11 am, where Arindam, Ihor, Carlo and Diana presented their work. Since I did not have that much of exposure in this particular area in my masters, so it was nice to know about the interesting problems they are working on, and various analytical approaches and methods.

2. By attending the internal seminars on Friday, by Daniel, Hee Chul and Sang-Jun, I got to know about their current works in detail.

3. In addition to this, I also attended a IBS Physics colloquium by Young-Kee Kim and PCS seminars by visitors Sergey Denisov and Satish Kumar.

4. I also attend Juzar's classes on open quantum systems every Thursday. This was another area, I did not know much about, so his lectures on basics in open quantum systems, are worth learning.

5. Informal discussions with students, research fellows and team leaders, were also a good learning experience for me.

6. I attended group meetings, which were more of a discussion session, where my team members, Ivan's PhD students presented their work. In the next group meeting, in the next week, I presented the work done in my masters.

7. I presented a talk on my recently published paper, at the CCMS-LUMIN team meeting. I got many valuable comments and feedback on my work, in this talk. In addition to that, I attended Friday internal seminars and visitor talks, which were a good learning experience for me.

Spin textures, beam shifts, and spin orbit interactions in structured elastic waves
Irving Rondón: February 1 – June 30, July 8 – October 8, 2019

Acoustic waves in synthetic vector potentials

We have been studying the propagation of small amplitude acoustic waves in a fluid with uniform density and a steady state velocity profile $\vec{u}$. We assume the fluid speed is much smaller than the speed of sound c, i.e. $u^2/c^2 \ll 1$, and that $\vec{u}$ has a slow spatial variation compared to the acoustic wavelength. Under these conditions, the acoustic velocity potential ϕ obeys the wave equation. Assuming an ambient medium with uniform density, the acoustic velocity potential ϕ obeys the wave equation

$$\nabla^2\phi - \frac{1}{c^2}D_t^2\phi = 0, \quad D_t = \partial_t - \vec{u}\cdot\nabla \tag{1}$$

where $c^2 = 1/(\rho\beta)$ is the speed of sound, determined by the mass density ρ and compressibility β. The local pressure $P(\vec{r},t)$ and particle velocity $\vec{v}(\vec{r},t)$ fields induced by the acoustic wave are given by $P = \rho D_t\phi$ and $\vec{v} = -\nabla\phi$. Eliminating ϕ yields the coupled first order equations

$$\beta D_t P = -\nabla\cdot\vec{v}, \quad \rho D_t\vec{v} = -\nabla P. \tag{2}$$

Using Eqs. (2) and the fact that $\nabla\cdot\vec{u} = 0$ for a steady state background flow, one can show that $(P,\vec{v})$ obey the continuity equation

$$D_t\left(\frac{\beta}{2}P^2 + \frac{\rho}{2}\vec{v}^2\right) + \nabla\cdot(P\vec{v}) = 0, \tag{3}$$

Specializing to monochromatic solutions $\phi(\vec{r},t) = \psi(\vec{r})e^{-i\omega t}$, using the approximation $u^2/c^2 \ll 1$, the acoustic wave equation can be written in term of the vector potential

$$\left(\nabla - i\vec{A}\right)^2 \phi + \frac{\omega^2}{c^2}\phi = 0, \quad \vec{A} = -\frac{\omega}{c^2}\vec{u}, \tag{4}$$

where the vector potential $\vec{A}$ given in term of the background fluid flow $\vec{u}$ resembling a vector potential in the time independent Schrödinger equation. Using Eq. (3) we can obtain, the time-averaged energy W and energy flux $\vec{\Pi}$ densities as

$$W = \frac{1}{4}(\beta|P|^2 + \rho|\vec{v}|^2), \tag{5}$$

$$\vec{\Pi} = \frac{1}{2}(\mathrm{Re}[P^*\vec{v}] + W\vec{u}). \tag{6}$$

We introduce a quantum-like formalism by defining the wavefunction $|\psi\rangle = (P,\vec{v})^T$ and inner product

$$\langle\Psi|\Psi\rangle = \frac{1}{4\omega}(\beta|P|^2 + \rho|\vec{v}|^2) \tag{7}$$

such that $W = \langle\Psi|\omega|\Psi\rangle$, independent of $\vec{u}$. Similarly, the canonical momentum density $\vec{p} = \langle\Psi|(-i\nabla)|\Psi\rangle$ which characterizes the local phase gradient remains,

$$\vec{p} = \frac{1}{4\omega}\mathrm{Im}[\beta P^*\nabla P + \rho\vec{v}^* \cdot (\nabla)\vec{v}], \tag{8}$$

where $\vec{v}^* \cdot (\nabla)\vec{v} \equiv \Sigma_j v_j^* \nabla v_j$, as in the electromagnetic case.

On the other hand, we found in our derivation the kinetic momentum density $\vec{\Pi}$ has an additional $\vec{u}$-dependent term, the relation between the canonical and kinetic momenta is modified as follows

$$\frac{\vec{\Pi}}{c^2} = \vec{p} - \frac{W}{\omega}\vec{A} + \frac{1}{4}\nabla\times\vec{S} - \frac{\rho}{4\omega}\mathrm{Re}[\vec{v}\times(\vec{v}\times\vec{A})], \tag{9}$$

where

$$\vec{S} = \frac{\rho}{2\omega}\mathrm{Im}(\vec{v}\times\vec{v}), \tag{10}$$

is the spin angular momentum density. The right hand side of Eq. (9) naturally separates into three terms: $\vec{p} - \frac{W}{\omega}\vec{A}$ is directly analogous to the usual relation between kinetic and canonical momenta in the scalar Schrodinger equation (since $W \to \omega$ in the scalar limit). The spin term is the spin contribution to the kinetic momentum. The final term is new, and forms an $\vec{A}$-dependent correction arising because Ψ is not a simple scalar field. Also in contrast to the Schrödinger equation, where the vector potential has a gauge freedom, here $\vec{A}$ is proportional to the background fluid velocity $\vec{u}$, which is a real and measurable gauge-invariant quantity. It is important to note that using Eq. (10) it is possible to obtain the Poynting vector as

$$\vec{p}_s = \frac{1}{4}\mathbf{Im}\nabla\times\vec{S}, \tag{11}$$

Finally, to complete the analysis, we will study the OAM density using the canonical and kinetic picture using (8) and (9) respectively

$$\vec{L} = \vec{r}\times\vec{p}, \quad \vec{M} = \vec{r}\times\vec{\Pi}. \tag{12}$$

In our problem, we will consider a background vortex flow of uniform density induced by rotation of two concentric cylinders of radii $R_{1,2}$, which can be described as $\vec{u} = (ar + b/r)\hat{e}_\theta$

where $a = \frac{\Omega_1\left(\frac{\Omega_2}{\Omega_1}-\left(\frac{R_1}{R_2}\right)^2\right)}{1-\left(\frac{R_1}{R_2}\right)^2}$ and $b = \frac{\Omega_2\left(R_1^2\left(1-\frac{\Omega_2}{\Omega_1}\right)\right)}{1-\left(\frac{R_1}{R_2}\right)^2}$ where $\Omega_{1,2}$ are the rotation frequencies of the cylinders. As noted above, $\vec{u}$ is analogous to a vector potential in the time independent Schrödinger equation. The time reversal symmetry breaking induced by Eq. (4) was used to obtain a phononic crystal with a topologically nontrivial band structure. There are two simple limits of Eq. (4). When $\Omega_2 = 0$, $\vec{u} \propto r$ resembles the vector potential describing a uniform magnetic field. On the other hand, when $\Omega_2 = R_1^2\Omega_1/R_2^2$ the second term dominates and we obtain a thin magnetic flux line at $r = 0$.

Acoustic vortex beams in synthetic magnetic fields

The problem was to analyzed the propagation of acoustic vortex beams in longitudinal synthetic magnetic fields. We showed how to generate two field configurations using a fluid contained in circulating cylinders: a uniform synthetic magnetic field hosting Laguerre-Gauss modes, and an Aharonov-Bohm flux tube hosting Bessel beams. For non-paraxial beams we find qualitative differences from the well-studied case of electron vortex beams in magnetic fields, arising due to the vectorial nature of the acoustic wave's velocity field. In particular, the pressure and velocity components of the acoustic wave can be individually sensitive to the relative sign of the beam orbital angular momentum and the magnetic field. Our findings illustrate how analogies between optical, electron, and acoustic vortex beams can break down in the presence of external vector potentials.

Our main conclusions in this research was the study of acoustic vortex beams in the presence of synthetic magnetic fields. We analyzed two simple limits; a uniform field and a flux tube, where the vortex beams can be obtained exactly from solutions of the radial Schrodinger equation. This enables a direct comparison between previously-studied optical and electron vortex beams. The main important differences are:

- The vector potential of the electronic Schrodinger equation is a gauge field, whereas the synthetic vector potential in acoustics is the gauge-invariant background fluid speed which must be slow compared to the acoustic wave speed. This limits acoustics to weak uniform synthetic magnetic fields, which can host weakly-localized (nearparaxial) Laguerre-Gauss beams.
- Beam symmetries present in the effective Schrödinger equation and total energy density W can be broken when considering the microscopic acoustic pressure P and velocity $\vec{v}$ fields. This is because the synthetic vector potential induces a redistribution of energy between P and .
- The synthetic magnetic fields can be used to fine-tune the beam profiles, and therefore control the distribution of the acoustic spin density in nonparaxial beams.

In the future it would be interesting to extend this analysis to acoustic surface waves, where analogies with surface plasmon polaritons have recently been explored. In particular, the breaking of time-reversal symmetry due to the synthetic magnetic field is expected to induce unidirectional surface wave propagation. Other interesting directions are the analysis of forces on small particles induced by structured acoustic beams and the characterization of random acoustic wave fields, including their distribution of phase and polarization singularities and emergence of superoscillations. Here we anticipate further non-trivial differences between the scalar effective Schrodinger equation governing the acoustic velocity potential and the real measurable pressure and velocity fields.

Acoustic super oscillations: the local wave vector

Recently, the authors have presented using first principles of fluid physics the most important properties for sound waves propagation, the transverse spin and surface waves in acoustic metamaterials, the spin and orbital angular momentum of acoustic beams. In these papers, the expression are naturally related with the pressure P and the velocity $\vec{v}$, the scope and prediction promise very interesting applications.

On the other hand a recent review about and a road map in super oscillation was reported, where the acoustic has a considerable space of research still to be done. With this motivation, we will continue our study related with super oscillation in acoustic fields, where it was shown how the local wave vectors effects can be related with super oscillations in random electromagnetic fields. These physical and analytical precedents insight provide us the possibility to study and explore acoustic super-oscillation. Then, our first step was build a random sample of plane waves by considering monochromatic approximation as

$$\psi = a_0 e^{-i\omega t} \sum_{j=1}^{N} e^{i\vec{k}_j \cdot \vec{r}}, \tag{13}$$

where a_0 is certain constant amplitude, the wave vector (phase factor) $i\vec{k}_j \cdot \vec{r}$ in random spherical coordinates. We propose to study acoustic super oscillation, where the local wave vector for a scalar and vector field are given by

$$P \equiv |\vec{k}_{sc}| = \mathbf{Im}\left[\frac{\psi^* \nabla \psi}{\psi^* \psi}\right] \text{(scalar)}, \quad \vec{v} \equiv \vec{k}_{\vec{v}} = \mathbf{Im}\left[\frac{\vec{v}^* \cdot (\nabla)\vec{v}}{\vec{v}^* \cdot \vec{v}}\right] \text{(vector)}. \tag{14}$$

where the sound velocity field is obtained as $\vec{v} = -\nabla\psi$ and $\vec{v}^* \cdot (\nabla)\vec{v} = v_x^* \nabla v_x + v_y^* \nabla v_y + v_z^* \nabla v_z$ in Cartesian coordinates.

In order to calculate the local wave vectors using Eq. (14) for both cases, we have been developing the numerical code to generated N = 100 of random plane waves with a uniform random sampling of 10,000 superposition. Currently, we have explore for the scalar case (pressure super oscillations), the results obtained are in agreement with the known result, also we have been working with the vector field (sound super oscillation). Here, it is important to mention that our case differ the reported results, in this work, the polarization was included since the problem was to study a random electromagnetic field. In our case we are interested in a random velocity field.

Many-body localization
Boris Altshuler: April 10 – May 13, 2019

The general field of the collaboration could be formulated as "Dynamical properties of classical and quantum non-integrable systems with large number of degrees of freedom". The central concepts in this field are integrability, localization and ergodicity. Dynamics of a classical integrable system are determined by the set of integrals of motion – quantities that remain constant during the time-evolution. The trajectory of the system in the phase space is thus confined to a hypersurface determined by a set of the integrals of motion. These integrals of motion for quantum integrable systems are quantum numbers characterizing the stationary quantum states. Violation of the integrability in the classical case eventually leads to the chaotic dynamics with the trajectories spread over the energy shell in the phase space. In quantum case this corresponds to the hybridization of the quantum states with different sets of quantum numbers. However the eigenstates become extended only when the violation of the Integrability is strong enough. For weaker violation the eigenstates remain localized in the space of quantum numbers. This genuine quantum phenomenon known as

Many-Body localization (MBL) is the analog of the celebrated Anderson Localization. An important difference of MBL from the conventional Anderson Localization is the structure of the extended states: they are likely to be far from ergodic, which probably requires reconsideration of the basic approaches of statistical physics. This might apply to both quantum and classical systems with large number of degrees of freedom close to the Integrability.

The first project Boris Altshuler was participating in aims to investigate the ergodicity and dynamics of a classical model of one-dimensional chain of coupled rotors. The advantage of this model is the existence of the quantum analog namely a Josephson array, which can be realized experimentally. In the limit of infinite energy per rotor angular momenta of each rotor is an integral of motion and the system can be considered as an integrable one. From the previous work of Sergej Flach and his collaborators it followed that at least at not too high energies the ergodicity (equivalence between the spatial and temporal averaging) indeed takes place but requires enormously long and quickly increasing with energy times. Alternatively in order to examine the ergodicity one can check the validity of general thermodynamic identities. States of a closed ergodic system, which energy is conserved form the micro-canonical ensemble. Consider a subsystem much smaller that the whole system - few rotors or even only one rotor. Can the subsystem after long enough evolution be viewed as a member of the canonical ensemble, i. e. be characterized by the temperature? If yes then e.g. both the average energy and the mean square of the energy of the subsystem would be fully determined by the temperature. Analysis of the numerical computations in which Boris Altshuler actively participated demonstrated that the subsystem is characterized by the distributions that can be called quasi-canonical: the canonical thermodynamic identities have definite corrections inverse proportional to the size of the whole system. The most interesting outcome of this analysis is the time-dependent relaxation of the mean-square energy: it was found that in spite of being extremely slow this relaxation is well described by the diffusion equation. As a byproduct of this analysis an alternative method of extracting transport properties of the system was developed. It is now clear that similar approach can be applied to a broad class of models, e.g. discrete non-linear Schrodinger equation. Most of the results of this project are already obtained and hopefully a manuscript will be prepared soon.

Another project, which was started during the visit of Boris Altshuler to PCS IBS is devoted to the Anderson model on a random regular graph. This problem although one-particle is carries the most of generic features of the non-ergodic many-body problems close to MBL transition. The crucially important characteristic of a non-ergodic quantum system is the fractal dimension of the eigenstates. The fractal dimension should vanish at the point of Anderson transition and tend to unity when the system becomes ergodic. Preliminary numerical results suggest that the dependence of fractal dimension on disorder is singular. Boris Altshuler in collaboration with Sergej Flach, Alexey Andrianov and Ihor Vakulchyk started a much more serious numerical studies aimed to understand the nature of these singularities and their influence of the physical properties of many-body systems.

In addition to working on these two projects Boris Altshuler during his stay at PCS IBS participated in discussion of several ongoing projects of PCS. One of them is the problem of two interacting quantum particles in one-dimensional random potential. As a result of these discussions dependences of the two-particle localization length on the strength of the interaction and on the energy became clearer.

Demonstrating quantum locality of the Aharonov-Bohm effect with mesoscopic superconducting devices
Kicheon Kang: January 1 – February 28, 2019

Constructing U(1) gauge theory based on local field interaction (LFI) approach

I have continued works on constructing the U(1) gauge symmetry on the basis of the local field interaction (LFI) approach. In the previous report, I discussed the invariance of the classical equation of motion under the "gauge transformation" of Π^μ, the field momentum. This symmetry is not associated with a redundancy as Π^μ is a physical quantity without any arbitrariness. Rather, a transformation of Π^μ corresponds to a change of the distribution in E and B. A constraint in the transformation is that the electromagnetic field tensor remains invariant.

Here I will describe the U(1) gauge symmetry for the scalar charge field interacting with the gauge field, ϕ. We begin with the Klein-Gordon equation for the field ϕ:

$$\left[-(\partial_\mu - \frac{i}{\hbar}\Pi_\mu)(\partial^\mu - \frac{i}{\hbar}\Pi^\mu) + \frac{m^2c^2}{\hbar^2}\right]\phi = 0. \tag{1}$$

Note that we can work on the Dirac field for the electron, but it leads to the same result concerning the U(1) gauge symmetry. The Klein-Gordon equation (Eq. (1)) for ϕ is generated by the Lagrangian

$$\mathcal{L} = -\frac{1}{m}(\hbar\partial_\mu\phi - i\Pi_\mu\phi)(\hbar\partial^\mu\phi^* + i\Pi^\mu\phi^*) - mc^2\phi^*\phi - \frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu}. \tag{2}$$

Mathematically, this Lagrangian contains all the properties that the standard Lagrangian for the charged field has (expressed in terms of A_μ instead of Π_μ). First, Lagrange equations for the fields ϕ and Π_μ lead to the Klein-Gordon and the Maxwell equations, respectively.

Second, and most importantly, the gauge symmetry in the Lagrangian of a charged field (Eq. (2)) is maintained in the invariance of $\mathcal{L}$ under the transformation

$$\phi \to \phi' = \phi e^{-i\Lambda/\hbar}, \quad \Pi_\mu \to \Pi'_\mu = \Pi_\mu - \partial_\mu\Lambda, \tag{3}$$

for any scalar function Λ. As in the case of the point particle discussed above, this symmetry bears no redundancy of description. Rather, it is a physical symmetry associated with different Π_μ, or equivalently, different distributions of external **E** and **B**. That is, the gauge symmetry in $\mathcal{L}$ states that *the equation of motion for ϕ (Eq. (1)) is invariant under change of the external electromagnetic field at a distance together with the modified phase factor of ϕ*. Finally, charge conservation is derived from the gauge symmetry through Nöther's theorem. In our framework with $\mathcal{L}$ of Eq. (2), it is expressed by the continuity equation

$$\partial_\mu j^\mu = 0, \tag{4}$$

of the four-charge current, j^μ

$$j^\mu = -i\frac{\hbar}{m}(\phi^* D^\mu\phi - \phi D^\mu\phi^*), \tag{5}$$

where the covariant derivative is given by

$$D^\mu\phi = (\partial^\mu - \frac{i}{\hbar}\Pi^\mu)\phi. \tag{6}$$

Byers-Yang theorem states that all physical properties of a doubly connected system (an annulus) enclosing a magnetic flux Φ are periodic in Φ with period $\Phi_0 = hc/e$. The theorem is demonstrated on the basis of the U(1) gauge symmetry. Here we show that the theorem can be generalized to an open system with our reconstruction of the gauge symmetry. Observational consequences of this generalization will also be discussed. In our language of the LFI approach, the eigenfunction of a charged particle in both systems satisfies

$$\frac{1}{2m}(-i\hbar\nabla - \Pi)^2\phi + c\Pi^0\phi = \epsilon\phi. \tag{7}$$

This is $v/c \ll 1$ limit of the Klein-Gordon equation. For many particles, the energy eigenfunction ψ satisfies

$$\frac{1}{2m}\sum_j(-i\hbar\nabla_j - \Pi(\mathbf{r}_j))^2\psi + V\psi = E\psi. \tag{8}$$

As the magnetic field vanishes in the region of nonzero ψ, $\nabla\times\Pi = (e/c)\mathbf{B} = 0$, and we can write $\Pi = \nabla\Lambda$. Under the transformation

$$\begin{aligned} \psi &\rightarrow \psi' = \psi e^{-(i/\hbar)\Sigma_j\Lambda(\mathbf{r}_j)}, \\ \Pi &\rightarrow \Pi' = \Pi - \nabla\Lambda = 0, \end{aligned} \tag{9}$$

the wave equation (8) reduces to

$$\frac{1}{2m}\sum_j(-i\hbar\nabla_j)^2\psi' + V\psi' = E\psi' : \tag{10}$$

Π is eliminated with a modified boundary condition for the wave function.

Consider the boundary condition of the doubly connected system. For any specific coordinates of a particle, say $\mathbf{r}_i$, circulated around once the loop while keeping all the other coordinates fixed, ψ' acquires a phase factor by the transformation (9) as

$$\psi' \rightarrow \psi' e^{-i\oint\Pi\cdot d\mathbf{r}/\hbar} = \psi' e^{-i(e\Phi/\hbar c)}. \tag{11}$$

The eigenvalues E are determined by the wave equation (8) and the boundary condition (11), and this constitutes the original Byers-Yang theorem: All the physical properties of the loop are periodic in the flux with its period $\Phi_0 = hc/q$.

In contrast to the conventional approach to the U(1) gauge symmetry, our analysis on the periodicity can be extended to an open system. The gauge transformation of Eq. (9) again transforms wave equation (8) into the wave equation of ψ' (Eq. (10)). For a specific coordinate of a particle, $\mathbf{r}_i$, let $\psi'_L(\psi'_R)$ be the asymptotic value of the wave function at the left (right) infinity,

$$\psi'_L \equiv \psi'(\mathrm{r}_i \rightarrow -\infty), \psi'_R \equiv \psi'(\mathrm{r}_i \rightarrow \infty). \tag{12}$$

From the gauge transformation (Eq. (9)), we find

$$\frac{\psi'_L}{\psi'_R} = \alpha e^{i\int_{-\infty}^{\infty}\Pi\cdot d\mathbf{r}/\hbar}. \tag{13}$$

The constant α is $\alpha = \psi'_L/\psi'_R$ when $\Pi = 0$. As the eigenvalue E is determined entirely by the wave equation (10) and the boundary condition (13), all physical properties are periodic in $\int_{-\infty}^{\infty}\Pi\cdot d\mathbf{r}/\hbar$ with period 2π. This constitutes the Byers-Yang theorem extended to an open system.

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 flat bands, disorder, one dimensional strongly correlated systems, driven quantum systems and topology. On the topics of flat bands and disorder there is active co-advising of the PhD student Yeongjun Kim (started in fall 2020).

Five publications were coauthored and published (3 in Physical Review B, 1 in Physical Review A and 1 in Nuclear Physics B journals):

- In PRB 104, L180201 (2021) we report on the discovery of a metal-insulator transition in very weakly disordered flatband systems: adding disorder to an insulator can result in a metal. Our results highlight and provide important insights into the physics of macroscopic degeneracies and the emerging phases when perturbing them: flatbands react sensitively and differently to seemingly similar very weak perturbations (see also two page summary within this scientific report).
- In PRB 103, 195129 (2021) we study the one-particle spectral functions in the one-dimensional half-filled Hubbard model in both zero and finite magnetic field. The one-particle excitations are gapped and exhibit fractionalization leading to the phenomenon of the spin-charge separation (see also two page summary within this scientific report).
- In PRB 103, 045118 (2021) and NPB 960, 115175 (2020) the spectra and role in the spin dynamical properties of bound states of elementary magnetic excitations named Bethe strings are studied. They occur in some integrable spin and electronic one-dimensional (1D) models and have recently been identified in several materials by experiments. In our works we study Bethe strings and their effects on the spin dynamical structure factor in a paradigmatic strongly correlated systems, the 1D Hubbard model at half filling (PRB) and the spin 1/2 Heisenberg XXX model (NPB). We find that the most significant spectral weight contribution from Bethe strings leads to a gapped continuum in the spectrum of the spin dynamical structure factor, which is very weakly dependent on the Coulomb repulsion strength U in the case of 1D Hubbard model.
- In PRA 102, 033106, (2020) we present the possibility of spin-dependent Kapitza-Dirac scattering based on a two-photon interaction only. The interaction scheme is inspired from a Compton scattering process, for which we explicitly show the mathematical correspondence to the spin dynamics of an electron diffraction process in a standing light wave. The spin effect has the advantage that it already appears in a Bragg scattering setup with arbitrary low field amplitudes, for which we have estimated the diffraction count rate in a realistic experimental setup at available x-ray free-electron laser facilities.

From Feb. 2020 he participated in 3 events:

- Jan. 15. 2021, contributed talk: Nodal loop semimetals in quasiperiodic potentials presented at "Mini Symposium on Topological Quantum Materials and Devices" at ITP CAS (virtual conference), Beijing, China
- Aug. 18. 2021, invited talk: Metal-Insulator transitions in infinitesimally weakly disordered flatbands at "IBS conference on Flatbands" at PCS IBS (virtual conference), Daejeon, Korea
- Sep. 27. 2021, poster: Metal-Insulator transitions in infinitesimally weakly disordered flatbands at "Non-equilibrium collective phenomena workshop" at Gyeongju, Korea

From January 2021 he took the duty of the PCS seminar master and hosted the PCS talks and colloquiums (in 2020 more than 70 seminars were presented in on-line form, most of which are archived and can be viewed at https://www.youtube.com/channel/UC0c8V38r5QOGgrlnsu-nREA).

Dr. Ki Hoon Le

Dr. Ki Hoon Lee joined the Center in January 2020 and was promoted as a distinguished PCS postdoctoral research fellow on May 11th of the same year. Getting that position was an objectively evident career advancement and gave him more confidence. Undoubtedly this confidence likely helped him get his next position, a tenure track faculty position at Incheon National University in Korea. As a result, unfortunately, he had to terminate the fellow position shortly on August 21st for his following career path. Unfortunately, due to the brevity of the term and the social distancing, there is not much academic activity to report. However, he has actively participated in the research and discussions as a member of Dr. Ara Go's strongly correlated electronic systems team. Also, he managed to publish or submit some papers during the period with his colleagues. Below are his publications during and just after his term as a distinguished Postdoc at IBS-PCS.

- Spin-orbit coupling effects on spin-phonon coupling in Cd2Os2O7, Phys. Rev. B 102 (20), 201101 (2020).
- Magnetoelastic excitations in multiferroic hexagonal YMnO3 studied by inelastic x-ray scattering, Phys. Rev. B 102 (8), 085110 (2020).
- Momentum-Dependent Magnon Lifetime in the Metallic Noncollinear Triangular Antiferromagnet CrB2, Phys. Rev. Let. 125 (2), 027202 (2020).

3.3 Appointments and Awards

Since the foundation of the PCS, nine 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.

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.*

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 currently hosts seven 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* 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

In response to the prolonged COVID-19 situation, we installed a hybrid conference system for video conferences in the PCS seminar room. The hybrid conference system consists of two screens, two projectors, a motion-tracking camera, a voice-tracking camera, and sound systems. When a video conference is held in the PCS seminar room, the speaker gives a talk using the presentation material on the main screen. The motion-tracking camera tracks the speaker's movements. The voice-tracking camera tracks the audience and zooms in on the the questioner. Presentation materials, speaker and audience video and audio signals are transmitted to online participants using a software for virtual conferences. The second screen is used to see both the online participants audience and the on-site audience in the PCS seminar room. In the future, the hybrid conference system in the PCS seminar room will be used to organize international workshops and seminars with other institutions in hybrid mode.

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 and second Scientific Advisory Board meetings took place in December 2016 and April 2019, whereas the next meeting is scheduled for 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
Mordechai Segev	Technion - Israel Institute of Technology, Israel

3.7 Members of the Center

(as of Dec. 31, 2021)

Position	No.
Director	1
Research Fellow	20
– Junior Research Team Leader	5
– Deputy Team Leader	1
Ph.D. Student	10
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	since 07/21	Ukraine	R	Quantum Many-Body Interactions and Transport
Jayendra Nath Bandyopadhyay	02/20 - 01/21	India	RF	Open Quantum Dynamics and Thermodynamics
Grigory Bednik	since 11/21	Russia	RF	Topological and Correlated Quantum Matter
Tilen Cadez	since 02/20	Slovenia	RF	Complex Condensed Matter Systems
Nana Chang	08/19 - 05/21	China	R	Complex Condensed Matter Systems
Sang-June Choi	11/17 - 08/19	Korea	RF	Quantum Many-Body Interactions and Transport
Carlo Danieli	11/16 - 11/19	Italy	RF	Complex Condensed Matter Systems

Barbara Dietz-Pilatus	since 07/21	Germany	RF	Complex Condensed Matter Systems & Quantum Chaos in Many-Body Systems
Henry Elsom	07/19 - 08/19	UK	R	Open Quantum Dynamics and Thermodynamics
Mikhail Fistul	01/17 - 01/20	Russia	RF	Complex Condensed Matter Systems
Sergej Flach	since 12/14	Germany	D	Complex Condensed Matter Systems
Ara Go	11/16 - 08/20	Korea	T	Strongly Correlated Electronic Systems
Niladri Gomes	01/19 - 12/19	India	RF	Strongly Correlated Electronic Systems
Sinan Gundogdu	09/19 - 06/21	Turkey	RF	Theoretical Photonics
Jae Ho Han	since 03/20	Korea	RF	Quantum Many-Body Interactions and Transport
Jungyun Han	since 03/18	Korea	R	Theoretical Photonics & Open Quantum Dynamics and Thermodynamics
Sarika Jalan	02/20 - 01/21	India	RF	Complex Condensed Matter Systems
Paulina Kaczynska	07/19 - 08/19	Ukraine	R	Complex Condensed Matter Systems
Hlib Kavatsiuk	07/19 - 08/19	Ukraine	R	Complex Condensed Matter Systems
Juyeon Kim	04/21 - 08/21	Korea	R	Quantum Chaos in Many-Body Systems
Kun Woo Kim	07/18 - 08/19	Korea	RF	Quantum Many-Body Interactions and Transport
Kyoung-Min Kim	since 03/20	Korea	RF	Strongly Correlated Electronic Systems & Topological and Correlated Quantum Matter
Yeongjun Kim	since 09/20	Korea	R	Complex Condensed Matter Systems
Dogyun Ko	since 03/18	Korea	R	Light-Matter Interaction in Nanostructures
Sergei Koniakhin	since 09/21	Russia	YSF	Optics of Quantum Fluids and Nanomaterials
Dominika Konikowska	04/16 - 05/20	Poland	RF	Visitor Program Coordinator

Hyeong Jun Lee	since 03/18	Korea	RF	Strongly Correlated Electronic Systems
Jaehyoung Lee	02/17 - 01/20	Korea	R	IT Manager
Ki Hoon Lee	01/20 - 08/20	Korea	RF	Strongly Correlated Electronic Systems
Minyoung Lee	since 06/16	Korea	RE	IT Manager
Sanghoon Lee	since 03/21	Korea	R	Complex Condensed Matter Systems
Woo Seok Lee	03/19 - 06/21	Korea	RF	Complex Condensed Matter Systems
Daniel Leykam	08/17 - 08/20	Australia	YSF	Theoretical Photonics
Wulayimu Maimaiti	10/15 - 04/20	China	R	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Merab Malishava	since 09/17	Georgia	R	Complex Condensed Matter Systems
Arindam Mallick	since 03/19	India	RF	Complex Condensed Matter Systems
Aleksandra Maluckov	01/20 - 1/21	Serbia	RF	Theoretical Photonics
Rohith Manayil	08/19 - 08/20	India	RF	Open Quantum Dynamics and Thermodynamics
Mohammad Mirzakhani	since 10/20	Iran	RF	Quantum Many-Body Interactions and Transport
Muhammad Taufiq Murtadho	since 03/21	Indonesia	R	Complex Condensed Matter Systems & Quantum Chaos in Many-Body Systems
Dillip Kumar Nandy	since 04/21	India	RF	Quantum Chaos in Many-Body Systems
Pramod Padmanabhan	01/18 - 08/20	India	RF	Theoretical Photonics
Anton Parafilo	since 09/18	Ukraine	RF	Quantum Many-Body Interactions and Transport
Hee Chul Park	since 11/16	Korea	T	Quantum Many-Body Interactions and Transport
Moonjip Park	since 04/21	Korea	RF	Topological and Correlated Quantum Matter
Seongjun Park	07/20 - 09/20	Korea	R	Open Quantum Dynamics and Thermodynamics
Dario Rosa	since 01/21	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	since 11/20	Czech	RF	Quantum Chaos in Many-Body Systems
Ivan Savenko	since 02/16	Russia	T	Light-Matter Interaction in Nanostructures
Vahid Shaghaghi	since 07/21	Iran	R	Quantum Chaos in Many-Body Systems
Varinder Singh	since 12/20	India	RF	Quantum Chaos in Many-Body Systems
Jeongrak Son	07/20 - 08/20	Korea	R	Quantum Chaos in Many-Body Systems
Kabyashree Sonowal	since 03/20	India	R	Light-Matter Interaction in Nanostructures
Meng Sun	02/16 - 10/21	China	RF	Light-Matter Interaction in Nanostructures
Juzar Thingna	02/19 - 09/21	India	YSF	Open Quantum Dynamics and Thermodynamics
Diana Thongjaomayum	04/17 - 04/20	India	RF	Complex Condensed Matter Systems & Strongly Correlated Electronic Systems
Mithun Thudiyangal	11/16 - 11/19	India	RF	Complex Condensed Matter Systems
Ihor Vakulchyk	since 10/16	Ukraine	R	Complex Condensed Matter Systems
Kristian Hauser A Villegas	05/17 - 05/19	Philippines	RF	Light-Matter Interaction in Nanostructures
Sungjong Woo	04/18 - 12/20	Korea	RF	Quantum Many-Body Interactions and Transport
Kati Yagmur	04/16 - 07/21	Turkey	R	Complex Condensed Matter Systems
Chang-Hwan Yi	since 04/21	Korea	RF	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Sukjin Yoon	10/16 - 01/19	Korea	RF	Light-Matter Interaction in Nanostructures

Chapter 4

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