2017 – 2018

SCIENTIFIC REPORT

Center for Theoretical Physics of Complex Systems
Institute for Basic Science

PCS Center for Theoretical Physics of Complex Systems

IBS Institute for Basic Science

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Contents

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 focussed 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.

Outlook: Our second IBS Young Scientist Fellow, *Juzar Thingna*, was selected in 2018 and started at the PCS in February 2019 his new YSF junior research team – *Nonequilibium Quantum Thermodynamics.* In 2019, the PCS will host the Advanced Study Group *Functional Spin-Active Mesoscopic Weak Links* and four international workshops. The Center currently has 34 members including Ph.D. students, and six research teams.

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, flat bands, 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.

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 2017 and 2018, 127 scientists visited the Center – also within special programs – with the addition of a total of 424 workshop participants.

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 2017–2018 we hosted scientists from 31 countries, benefitting 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). We also maintain close relations with other IBS centers.

Institutional networking is currently realized mainly through joint international workshops held predominantly at the PCS. In 2017, the PCS was in charge of the Pioneer Symposium *Nonlinear dissipative quantum Bose-Einstein condensates* during the Korean Physical Society (KPS) Spring Meeting, and we organized the International Workshop *Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems* in cooperation with the APCTP and ICTP. In 2018, the PCS conducted the International Workshops *Disordered Systems: From Localization to Thermalization and Topology* and *Attosecond Physics at the Nanoscale* assisted by the APCTP and CASTECH (Center for Attosecond Science and Technology, MPK, Pohang), respectively, whereas together with MPK (Max Planck POSTECH/Korea Research Initiative) we supported the APCTP workshop on *spin-orbit coupled topological states*. In 2019, we will host the first IBSPCS-KIAS International Workshop *Frustrated Magnetism* whereas MPK, Kunsan National University (Gunsan), and the ICTP will contribute to our International Focus Workshop *Computational Approaches to Magnetic Systems*.

Internationally, numerous scientific collaborations connect the PCS with many distinguished institutions worldwide, including École Polytechnique (France), University of Cambridge (UK), STFC Rutherford Appleton Laboratory (UK), Johannes Gutenberg University of Mainz (Germany), University of Würzburg (Germany), University of Augsburg (Germany), ICTP (International Centre for Theoretical Physics, Italy), University of Trento (Italy), Catholic University of the Sacred Heart (Italy), University of Gothenburg (Sweden), NORDITA (Nordic Institute for Theoretical Physics, Sweden), University of Eastern Finland (Finland), IQOQI (Institute for Quantum Optics and Quantum Information, Austria), EPFL (École Polytechnique Fédérale de Lausanne, Switzerland), National Technical University of Athens (Greece), University of Ioannina (Greece), Ivane Javakhishvili Tbilisi State University (Georgia), Tel Aviv University (Israel), Technion - Israel Institute of Technology (Israel), Boston University (USA), Columbia University (USA), Santa Fe Institute (USA), University of Massachusetts Boston (USA), State University of New York at

Buffalo (USA), OIST (Okinawa Institute of Science and Technology, Japan), University of Tsukuba (Japan), Nanyang Technological University (Singapore), Australian National University (Australia), University of Wollongong (Australia), National Autonomous University of Mexico (Mexico), Zhejiang University (China), Donghua University (Shanghai, China), University of Calcutta (India), Novosibirsk State Technical University (Russia), ITMO University (Russia), Nazarbayev University (Kazakhstan), Nankai University (China), JINR (Russia), N.I.Lobachevsky State University of Nizhny Novgorod (Russia), Kirensky Institute of Physics (Russia), University of Bonn (Germany), RIKEN (Japan), University of Cape Town (South Africa), Bogolyubov Institute for Theoretical Physics (Ukraine), Northwestern Polytechnical University (China), Indian Institute of Science Education and Research Bhopal (India), Max Planck Institute for the Physics of Complex Systems (Germany), University of Waterloo (Canada), University of Innsbruck (Austria), University of Bordeaux (France), Lanzhou University (China), CAS Institute of Physics (China), Wuhan University of Technology (China), University of Chile (Chile), Loughborough University (UK), University of Toronto (Canada), Tohoku University (Japan), City University of New York (USA), RAS Institute of Applied Physics (Russia), University of Belgrade (Serbia), University of Maryland (USA), Washington University in St. Louis (USA), Waseda University (Japan), Karlsruhe Institute for Technology (Germany), Russian Quantum Center (Russia), Friedrich Schiller University Jena (Germany), Ruhr University Bochum (Germany), CNR-SPIN (Italy), National University of Science and Technology MISiS (Russia).

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) 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).

1.6 Division Complex Condensed Matter Systems

Director: Sergej Flach

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

1.6.1 Complex Condensed Matter Systems

Team Leader: Sergej Flach, Alexei Andreanov (deputy)

Research Topics

Nonequilibrium Many-Body Dynamics. Quantum interacting many-body systems are usually assumed to thermalize efficiently. Nonlinear many-body dynamical systems were known to show different outcomes related to the Kolmogorov-Arnold-Moser theorem and Arnold diffusion, due to the presence of invariant tori and the closeness to integrable systems. A plethora of physical systems allows for low-dimensional coherent states (e.g. simply periodic orbits) to persist astonishingly far away from these integrable limits. Recent progress e.g. in the field of many-body localization closes the gap and paves the way to study weakly ergodic and even nonergodic interacting many-body systems. Applications and rewards are expected to be located e.g. in the area of quantum computations. We explore the ways nonlinear dynamics is destroying wave coherence through deterministic chaos, and how many surrogate external ac fields it takes to replace that intricate effect. We started to explore the connection between quantum glasses, many-body localization 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. Main results:

- *Interacting ultracold atomic kicked rotors: dynamical localization*
  Scientific Reports 7, 41139 (2017)
- *Quantum subdiffusion with two- and three-body interactions*
  Eur. Phys. J. B 90, 66 (2017)
- *Intermittent many-body dynamics at equilibrium*
  Phys. Rev. E 95, 060202 (2017)
- *Quantum jumps on Anderson attractors*
  Phys. Rev. B 97, 020301(R) (2018)

- *Weakly Nonergodic Dynamics in the Gross-Pitaevskii Lattice*
  Phys. Rev. Lett. 120, 184101 (2018)
- *Signatures of many-body localization in steady states of open quantum systems*
  Phys. Rev. B 98, 020202(R) (2018)
- *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)

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:

- *Localization of weakly disordered flat band states*
  Eur. Phys. J. B 90, 1 (2017)
- *Fractional lattice charge transport*
  Scientific Reports 7, 40860 (2017)
- *Compact localized states and flatband generators in one dimension*
  Phys. Rev. B 95, 115135 (2017)
- *Chiral Flat Bands: Existence, Engineering and Stability*
  Phys. Rev. B 96, 161104 (2017)
- *Topological flat Wannier-Stark bands*
  Phys. Rev. B 97, 045120 (2018)
- *Compact Discrete Breathers on Flat Band Networks*
  Low Temperature Physics 44, 865 (2018)
- *Perspective: Photonic flatbands*
  APL Photonics 3, 070901 (2018)

- *Artificial flat band systems: from lattice models to experiments*
  Advances in Physics: X, 3:1, 1473052 (2018)
- *Fano Resonances in Flat Band Networks*
  Springer Series in Optical Sciences 219 (2018)
- *Excitation of localized condensates in the flat band of exciton-polariton Lieb lattice*
  Phys. Rev. B 98, 161204(R) (2018)
- *Molecular Kondo effect in flat-band lattices*
  Phys. Rev. B 97, 155125 (2018)
- *Unconventional Flatband Line States in Photonic Lieb Lattices*
  Phys. Rev. Lett. 121, 263902 (2018)
- *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)

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

- *Anderson localization in generalized discrete time quantum walks*
  Phys. Rev. B 96, 144204 (2017)
- *Almost compact moving breathers with fine-tuned discrete time quantum walks*
  Chaos 28, 123104 (2018)
- *Wave Packet Spreading with Disordered Nonlinear Discrete-Time Quantum Walks*
  Phys. Rev. Lett. 122, 040501 (2019)

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:

- *Stability through asymmetry: Modulationally stable nonlinear supermodes of asymmetric non-Hermitian optical couplers*
  Phys. Rev. A 95, 063832 (2017)
- *Flat bands in lattices with non-Hermitian coupling*
  Phys. Rev. B 96, 064305 (2017)
- *Amplitude death in a ring of nonidentical nonlinear oscillators with unidirectional coupling*
  Chaos 27, 083119 (2017)

- *Quantum Transport and Non-Hermiticity on Flat-Band Lattices*
  J. Low Temp. Phys. 191, 49 (2018)
- *Husimi functions at gradient index cavities designed by conformal transformation optics*
  Optics Express 26, 6851 (2018)

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, the dynamics of superfluid Fermi gases, metal-insulator transitions with Luttinger liquids, and superconducting qubit studies, among others. Main results:

- *Small-angle scattering from the Cantor surface fractal on the plane and the Koch snowflake*
  Phys. Chem. Chem. Phys. 19, 2261-2268 (2017)
- *Quantum Performance of Thermal Machines over Many Cycles*
  Phys. Rev. Lett. 118, 050601 (2017)
- *Scattering from surface fractals in terms of composing mass fractals*
  J. Appl. Cryst. 50, 919-931 (2017)
- *Pairing Dynamics of Polar States in a Quenched p-wave Superfluid Fermi Gas*
  Phys. Rev. Lett. 119, 100401 (2017)
- *Metal-insulator transition in a sliding Luttinger liquid with line defects*
  Phys. Rev. B 96, 165111 (2017)
- *Magnetically induced transparency of a quantum metamaterial composed of twin flux qubits*
  Nature Communications 9, 150 (2018)
- *Accurate projective two-band description of topological superfluidity in spin-orbit-coupled Fermi gases*
  SciPost Phys. 5, 016 (2018)
- *Circuit Quantum Electrodynamics of Granular Aluminum Resonators*
  Nature Communications 9, 3889 (2018)

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 discrete time quantum walks. On the division level, we broadened our spectrum with attractive projects in the field of strong electronic correlations, topological and non-Hermitian photonics, as well as nonequilibrium quantum thermodynamics. One of our next goals is to expand our spectrum of activities by adding the fields of quantum information and machine learning. This can happen both through consolidating the existing research and establishing a new team.

Cooperations

Within the PCS, we collaborate with all junior research teams. Strong cooperations inside Korea include 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 focusses on the quantum transport of mesoscopic systems and the quantum many-body interactions with mean field theory. In condensed matter physics, 2D materials – including graphene – have been intensively studied in terms of the optical, electrical, and mechanical degrees of freedoms. The spin-orbit interaction impacts a number of well-known physical phenomena, such as 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. Strain on graphene creates a strong pseudo-magnetic field due to the gauge potential acting on the valley-isospin of graphene.

- *Conductance oscillations at the junctions of Chern insulators: Valley-isospin dependence and Aharonov-Bohm effects*
  Phys. Rev. B 96, 235435 (2017)
- *Gas molecule sensing of van der Waals tunnel field effect transistors*
  Nanoscale 9, 18644-18650 (2017)
- *Strain-shear coupling in bilayer MoS2*
  Nature Communications 8, 1370 (2017)
- *Direct Probing of the Electronic Structures of Single-Layer and Bilayer Graphene with a Hexagonal Boron Nitride Tunneling Barrier*
  Nano Letters 17, 206-213 (2016)

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.

- *Mechanically driven spin-orbit-active weak links*
  Low Temperature Physics (Fizika Nizkikh Temperatur) 44, 12 (2018)
- *Mechanically induced thermal breakdown in magnetic shuttle structures*
  New Journal of Physics 20, 063036 (2018)
- *Strong two-mode parametric interaction and amplification in a nanomechanical resonator*
  Phys. Rev. Applied 9, 064023 (2018)
- *Transition of a nanomechanical Sharvin oscillator towards the chaotic regime*
  New Journal of Physics 19, 033033 (2017)

Quantum transport. We are interested in the fundamental quantum effects, such as the quantum resonances, quantum chaos, dynamical localization, quasi-periodicity and disorder, chirality of dynamic states, bulk-boundary correspondence of topological systems, and non-Hermitian systems. From graphene to ultra-cold atoms, from the prototypes of the simplest to the most exotic materials, our efforts to understand the fundamental properties of a variety of research topics in mesoscopic physics will be continued. 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.

- *Quantum Transport and Non-Hermiticity on Flat-Band Lattices*
  J. Low Temp. Phys. 191, 49-60 (2018)
- *Reconfiguration of quantum states in PT-symmetric quasi-one dimensional lattices*
  Scientific Reports 7, 8746 (2017)
- *Antiresonance induced by symmetry-broken contacts in quasi-one-dimensional lattices*
  Phys. Rev. B 96, 125421 (2017)
- *Compact localized states and flatband generators in one dimension*
  Phys. Rev. B 95, 115135 (2017)
- *Interacting ultracold atomic kicked rotors: dynamical localization*
  Scientific Reports 7, 41139 (2017)

Perspectives

Our research team was formed in May 2015 with Pinquan Qin and the team leader Hee Chul Park, and now consists of five collaborating members, including an associate member, Jung-Wan Ryu. Sungjong Woo is interested in the strain engineering on low dimensional materials for topological polarization. Sang-Jun Choi studies mesoscopic Majorana physics. Kunwoo Kim works on quantum field theory for condensed matter physics and topology. Anton Parafilo has joined us recently. His main research interest is the nanomechanical system, including Kondo effect and spin-orbit interaction. Jung-Wan Ryu is an expert in nonlinear oscillatory systems and microcavities. All the members work collaboratively on the topic of non-Hermiticity, 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 the 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) and Ilias Amananditis (postdoctoral researcher at Ben-Gurion University of the Negev, Israel). They still keep collaborating intensely with the team.

Collaborations

Outside of our Center, we have numerous collaborators with various universities and institutes worldwide. 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); 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).

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.*

- With *Meng Sun,* we considered exciton-photon coupling in semiconductor microcavities where separate periodic potentials have been embedded for the excitons and photons. We showed that this system supports degenerate ground-states appearing at non-zero in-plane momenta.
  – Scientific Reports 7, 45243 (2017)
- We investigated the magnetoplasmon Fano resonance in a hybrid system consisting of spatially separated two-dimensional layers of electron and dipolar exciton gases.
  – Phys. Rev. B Rapid Communications 94, 241408 (2016)
- With collaborators from Russia, we studied the pseudo-spin density response of a disordered two-dimensional spin-polarized Bose gas to a weak alternating magnetic field, assuming that one of the spin states of the doublet is macroscopically occupied and Bose-condensed, while the occupation of the other state remains much smaller.
  – Scientific Reports 7, 2076 (2017)
- With collaborators from Singapore and the UK, we developed a kinetic Monte Carlo approach for the description of nonequilibrium bosonic systems, taking nonresonantly excited exciton-polariton condensates and bosonic cascade lasers as examples.
  – Phys. Rev. B 96, 125423 (2017)
- With experimental collaborators from Germany, we studied the influence of spatial confinement on the second-order temporal coherence of the emission from a semicon-

ductor microcavity in the strong coupling regime.
– Phys. Rev. Letters 120, 017401 (2018)

- With a collaborator from Austria, we studied the Frenkel exciton-polariton Bose-Einstein condensation in a two-dimensional defect-free triangular photonic crystal with an organic semiconductor active medium containing bound excitons with dipole moments oriented perpendicular to the layers.
  – New Journal of Physics 20, 013037 (2018)
- We investigated the processes of electron capture by a Coulomb impurity center residing in a hybrid system consisting of spatially separated two-dimensional layers of electron and Bose-condensed dipolar exciton gases coupled via the Coulomb forces.
  – Phys. Rev. B 97, 165305 (2018)
- We developed a microscopic theory of the photon drag effect that appears in a Bose-Einstein condensate of neutral particles, considering indirect excitons in a double quantum well nanostructure under the action of a polarized electromagnetic field.
  – Phys. Rev. B 98, 041304(R) (2018)
- We developed a theory of the photovoltaic valley-dependent Hall effect in a two-dimensional Dirac semiconductor subject to an intense near-resonant electromagnetic field.
  – New Journal of Physics 20, 083007 (2018)
- With *Kristian Villegas*, we proposed an effective optical approach to monitor superconductors in a two-layer superconductor-normal metal structure.
  – Phys. Rev. B 98, 064502 (2018)
- We developed a microscopic theory of the photon drag effect which can occur in a general system containing Bose-Einstein condensed particles, possessing an internal structure of quantum states.
  – Phys. Rev. B 98, 165405 (2018)
- With *Meng Sun,* we proposed a way to directly excite compact localized condensates in a nearly flat band of the exciton-polariton Lieb lattice by short Laguerre-Gaussian pulses, and investigated the dynamics of these condensates in the presence of repulsive polariton-polariton interactions and distributed losses in the lattice.
  – Phys. Rev. B 98, 161204(R) (2018)
- With *Meng Sun* and *Sukjin Yoon,* we demonstrated the reconstruction of the exciton-polariton condensate loaded in a single active miniband in one-dimensional microcavity wires with a complex-valued periodic potentials.
  – arXiv:1806.03070
- We calculated a light-induced electric current which can occur from a Bose-Einstein condensate under the action of an external electromagnetic field with the frequency exceeding the ionization potential of the bosons, taking a system of indirect excitons as a testbed.
  – Phys. Rev. B Rapid Communications 98, 201405(R) (2018)
- With *Meng Sun* and *Kristian Villegas,* we discovered an unconventional mechanism of electron scattering in graphene in hybrid Bose-Fermi systems.
  – arXiv:1811.09373

Future Prospects

From the general perspective, we plan to *hire more people* in the group (Ph.D. students and postdoctoral researchers). Beside focussing on the scientific work, we plan to participate in several conferences (in particular, PLMCN and META). Moreover, we are currently organizing a workshop "International Workshop Spintronics and Valleytronics of Two-dimensional Materials" to be held at the PCS in May 2019.

The *scientific plans* include:

- With *Dogyun Ko* and *Meng Sun,* we are working on topological physics in the exciton-polariton microcavities with embedded complex-valued potentials, where we are considering a time-reversal symmetry breaking by means of the imaginary part of the potential. The plan is to study the complex eigenvalues and check the possibility of launching edge currents in such a system.
- With *Dogyun Ko* and *Meng Sun,* we are working on creation and manipulation of compact localised states (condensates) in exciton-polariton kagome lattices, using the driven-dissipative Gross-Pitaevskii equation approach and Laguerre-Gaussian pumping. We want to investigate the effect of the spin-orbital splitting (TE-TM) and nonlinearities on the flat band behavior and transport in this system.
- With *Meng Sun* and *Kristian Villegas,* we study the finite-temperature electron conductivity in graphene placed in the vicinity of a two-dimensional indirect exciton gas in the Bose-condensed phase. The electrons in graphene are coupled to excitons via the Coulomb interaction. We are aiming at double-bogolon processes.
- With *Meng Sun* and *Kristian Villegas,* we plan to study the finite-temperature electron conductivity in a two-dimensional electron gas placed in the vicinity of a two-dimensional indirect exciton gas in the Bose-condensed phase, and consider the double-bogolon mediated scattering.
- With *Kristian Villegas,* we are working on an amplifier of electromagnetic radiation, which can operate in a very large domain – from optics to microwaves, including terahertz frequencies. The device is based on a graphene-superconductor hybrid system. The mechanism of such a THz waves amplification is based on the quantum capacitance of graphene.
- We aim at developing a microscopic theory of the photon drag effect in superconductors. With *Kristian Villegas,* using the effective field theory approach, we have already understood that Cooper pairs in superconductors can exhibit a photon drag effect being subject to an external electromagnetic field with a finite in-plane momentum.
- We intend to establish a microscopic theory of the Coulomb drag effect in a hybrid system consisting of the spatially separated two-dimensional quantum gases of degenerate electrons and dipolar excitons.
- We plan to study the two-bogolon mediated superconductivity. In conventional theories, the phonon-related mechanism of electrons pairing is well known. Two-phonon pairing is not interesting due to the weakness of such processes. However, two-bogolon processes (where the excitations of the condensate called bogolons are substituting for acoustic phonons in a sense) have outstanding impact on the physics in hybrid systems.

1.6.4 Strongly Correlated Electronic Systems

Team Leader: Ara Go

Strong correlations induce various emergent phenomena, which make correlated systems fascinating research targets. Theoretical studies on those systems are often challenged by the underlying complexity. Any attempts to solve correlated systems directly encounter exponential computation costs, whereas exact solutions are limited to very small systems which are mostly inadequate for describing realistic systems. When the direct attack fails, the key is to capture the most important physical properties by well-designed, appropriate approximations. Furthermore, controlled numerical methods are on a high demand when aiming at a quantitative understanding of correlated systems.

The team consists of three members, Diana Thonjaomayum (jointly with the team "Complex Condensed Matter Systems"), Hyeong Jun Lee, and Niladri Gomes (since February 1st, 2019), and the team leader – Ara Go. We investigate strongly correlated electronic systems focusing on computational aspects: the implementation and application of numerical techniques, and the development of new algorithms to solve quantum many-body systems.

Research Topics

Dynamical mean-field theory and impurity solvers. The quantum impurity model describes systems where an impurity including a small number of correlated orbitals is embedded in the environment which is non-correlated but has much more degrees of freedom. Since it was proposed to explain the behavior of dilute magnetic impurities in metallic hosts, impurity models have given great insights into condensed matter physics problems as reasonable simplifications of reality, including: Kondo effect, core-level spectroscopy, and even in the nonequilibrium context, transport through quantum dots. The appearance of the dynamical mean-field theory (DMFT) also raised the importance of impurity solvers by establishing the self-consistency between a large intractable problem and a manageable impurity model. Obtaining accurate solutions of an impurity model for a wide frequency range is therefore vital to better understand the properties of many correlated systems. The DMFT has proven its power by successfully explaining emergent behaviors in correlated systems, specifically, transition metal oxides. However, the DMFT has not reached its full potential due to imperfection of the existing impurity solvers. For example, multi-orbital systems are challenging targets to be addressed – except for a few cases where an optimal solving way does exist. As most of correlated materials involve multiple orbital degrees of freedom, development of improved impurity solvers becomes one of the main tasks of the DMFT community. We work on the development, implementation, and optimization of impurity solvers in order to enhance the capability of the DMFT methodology. In the long term, a more capable impurity solver will contribute to the research on related systems.

Local correlation effects in spin-orbit coupled multi-orbital systems. After the discovery of topological insulators, Spin-orbit coupled multi-orbital systems have been an ideal playground for studying the exotic phases originating from the entanglement between the spin and orbital degrees of freedom. The aforementioned impurity solver combined with the dynamical mean-field theory is a useful tool to investigate materials where local correlations play a crucial role. Our impurity solver has advantages in obtaining solutions in the presence of a spin-orbit coupling at zero or very low temperature. We apply the DMFT method to spin-orbit coupled systems in order to describe various exotic phenomena, such as unconventional superconductivity, Hund's metallic behavior, interaction induced topological transitions, among others.

Spectral properties and response functions based on the electronic structure of correlated materials. One practical information obtained about realistic correlated systems is the response function measured in experiments. The precise computation of the response function of a well-defined correlated Hamiltonian is the key to material design with desired properties. We develop computational tools to calculate the response functions of correlated systems, corresponding to various experimental measurements, such as angle resolved photoemission spectroscopy, optical conductivity, and generalized susceptibility.

Deconfined-confined phase transition. The transition between a confined and deconfined phases is one of the best examples for emergent phenomena in correlated systems that cannot be explained by the single-particle approaches. This complexity makes the understanding of these transitions typically counter-intuitive. For instance, the spin-charge separation, which is commonly observed in one-dimensional correlated electronic systems, involves fractionalization of electrons, which is difficult to imagine solely based on the character of a single electron. Numerical approaches give us a shortcut to develop intuition and guidance to identify the interesting transitions. To study them, we employ many numerical techniques (exact diagonalization, mean-field approximations, Monte Carlo methods, and so on).

Collaborations

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

- Spin-orbit coupled spinel
  – IBS-CCES, Korea (Prof. Jegeun Park, Dr. Choong Hyun Kim)
  – UNIST, Korea (Prof. Hosub Jin)
- Spectral properties of Iridates
  – Columbia University, USA (Prof. Andrew Millis)
  – University of Toronto, USA (Prof. Yong Baek Kim)
- Density functional theory plus dynamical mean-field theory
  – KAIST, Korea (Prof. Myung Joon Han)
- Deconfined-confined phase transition
  – KAIST, Korea (Prof. Eun Gook Moon)

Future Perspectives

Numerics provides an intuitive and quantitative understanding of nontrivial problems, such as emergent phenomena in strongly correlated systems. Considering the rapid improvement of computing hardware, the prospects are bright for numerics combined with insightful approximations. However, the improved hardware leads to a better outcome only in combination with appropriate software and professional expertise. We will contribute to this field by training experts, developing tools, and applying them to understand the nature of correlated systems.

1.6.5 Theoretical Photonics

Team Leader: Daniel Leykam

The activities of the group started in August 2017 with the arrival of the team leader, Daniel Leykam. A Ph.D. Student, Jungyun Han, and a Research Fellow, Pramod Padmanabhan, joined in March and April 2018, respectively. Since November 2018, we have hosted Irving Rondón as a visiting research fellow.

Research output of the group numbers 15 publications, including 1 in *Nature Communications*, 3 in *Physical Review Letters*, and 3 invited reviews.

We presented at 9 international conferences and workshops: Optics and Photonics Symposium at Nankai University (Tianjin, China, October 2017), Quantum Nonlinear Optics 2018 (Kuala Lumpur, Malaysia, February 2018), International Symposium on Nanophotonics and Metamaterials (St Petersburg, Russia, June 2018), International Workshop "Exactly Solvable Quantum Chains" (Natal, Brazil, June 2018), IEEE Photonics Society Summer Topicals Meeting (Waikoloa, USA, July 2018), CLEO: Pacific Rim (Hong Kong, August, 2018), ICTP Asian Network School on Complex Condensed Matter Systems (Hanoi, Vietnam, November 2017 & Nakhon Ratchasima, Thailand, November 2018), Simons Center

Wokshop: Entanglement and Dynamical Systems (Stony Brook, USA, December 2018).

We also presented at the following domestic conferences: Korean Physical Society Spring Meeting (Daejeon, April 2018), Optical Society of Korea Summer Meeting (Busan, August 2018), International Workshop "Disordered Systems: From Localization to Thermalization and Topology" (Daejeon, September 2018), Workshop on Spin-Orbit Coupled Topological States (Pohang, October 2018).

Research Topics

The research of the group spans nonlinear and quantum photonics, with particular emphasis on light propagation in coupled waveguide or resonator lattices, and demonstration of novel topological phenomena. Specific research topics include:

Coupled resonator optical waveguides. Presently, coupled-resonator optical waveguides suffer from an intrinsic fabrication disorder, which limits their length and ability to faithfully transmit signals. We are interested in using the next-nearest-neighbour coupling as a means to achieve a disorder-robust light propagation in this platform, exploring two-dimensional and quasi-one-dimensional designs that are protected against the dominant sources of disorder.

Optically-induced photonic lattices. The optical induction technique provides a simple and effective method for creating a variety of nonlinear photonic lattice structures. We study novel effects including pseudospin-mediated phenomena in photonic graphene and unconventional localized modes in photonic flat band lattices, which have been observed by our experimental collaborators. This work helps to better understand analogous effects in two-dimensional materials such as graphene.

Nonlinear and quantum topological photonics. At the linear, single particle level, topological photonic systems closely resemble their electronic condensed matter counterparts, e.g. they share the same Bloch band structure. In the nonlinear or quantum regimes, these analogies break down and entirely new phenomena with no analogue in condensed matter systems can emerge. We theoretically investigate propagation of entangled photon pairs, nonlinearity-induced topological transitions, solitons, lasing, and the third harmonic generation in topological photonic lattices.

Supersymmetric lattice models. Supersymmetry (SUSY) was originally developed in the context of quantum field theory, but more recently it has been applied to design exactly solvable quantum spin chain models and novel photonic lattices such as coupled laser arrays. We study generalizations of SUSY in these contexts, including para-SUSY, higher-order SUSY, and supercharge models, with applications including the high power single mode lasing.

Classical optics. We have recently analyzed the surface waves of the simplest possible optical systems – uniform isotropic media – discovering that their phase diagram can be explained in terms of the recently-developed non-Hermitian topological band theory. We are interested in generalizing this result to anisotropic optical media, acoustics, and other continuum wave systems with spin-orbit coupling.

Collaborations

We have several successful international collaborations resulting in peer-reviewed publications:

- Zhigang Chen (Nankai University, China) – optically-induced photonic lattices,

- Yuri Kivshar (Australian National University, Australia) – nonlinear metasurfaces,
- Konstantin Bliokh, Clemens Gneiting, Franco Nori (RIKEN, Japan) – topological photonics,
- Yidong Chong (Nanyang Technological University, Singapore) – nonlinear photonics,
- Daria Smirnova (Russian Academy of Sciences, Russia) – nonlinear photonics,
- Mohammad Hafezi, Sunil Mittal (University of Maryland, USA) – ring resonator lattices,
- Aleksandra Maluckov (University of Belgrade, Serbia) – nonlinear flatband lattices,
- Lan Yang (Washington University in St. Louis, USA) – nonlinear photonics,
- Alexander Khanikaev (City University of New York, USA) – photonic crystals,
- Max Lein (Tohoku University, Japan) – topological photonics,

with the first two being experimental collaborations.

Future Perspectives

Quantum topological photonics is attracting increasing interest, with a few landmark experiments, such as the photon pair generation published, over the past year. We plan to focus more in this direction, exploring effects such as Hong-Ou-Mandel interference of topological edge states. A second direction will be to initiate studies of superconducting microwave qubit lattices, with the aim of exploring interactions in the quantum limit, and developing a realistic proposal to implement SUSY spin chain models in experiments.

A high priority in the coming year will be to strengthen domestic experimental collaborations. We have had preliminary discussions and seminar visits with a few local groups:

- Kyunghwang Oh (Yonsei University) – photonic crystals
- Jin-Kyu Yang (Kongju University) – photonic crystal lasers
- Namkyoo Park (Seoul National University) – supersymmetric photonics

In addition, we are organising the International Workshop *Recent Advances in Topological Photonics* to be held in Daejeon in June 2019, which will provide a venue for local and international researchers to exchange ideas and forge collaborations.

Our highly fruitful collaboration with the group of Prof. Zhigang Chen will continue, with experiments including light propagation in optically-induced kagome lattices already underway.

Chapter 2

Selection of Research Results

Contents

2.1 Dynamical glass in interacting many-body systems

C. Danieli, T. Mithun, Y. Kati, S. Flach

The core concepts in statistical physics known as the *ergodic hypothesis* assumes that during its evolution a system visits almost all available states and the infinite time average of any observable matches its microcanonical average. The corresponding time scale on which these properties manifest (the *ergodization time* T_E) may depend on the existence and the distribution of metastable states during the microcanonical dynamics of a system. Indeed their existence led to the first observation of glassy dynamics [1] (also dubbed *weak ergodicity breaking* [2]) in the case of divergent average lifetime. These states also exist in weakly non-integrable Hamiltonian systems in the form of long-lasting breather-like excitations [3]. The way these excitations affect the equilibrium dynamics and set the ergodization time T_E are core goals of our current research. In order to address them, we considered a set of classical thermalized many-body systems in the proximity of their integrable limits, namely the Fermi-Pasta-Ulam chain (**FPU**), the discrete non-linear Schrödinger system (**DNLS**), networks of Josephson junctions (**JJ**), and the Klein-Gordon lattice (**KG**) [4–7]. Therein, these models may be rewritten as

$$H(J,\theta) = H_0(J) + \varepsilon H_1(J,\theta)\ , \quad 0 < \varepsilon \ll 1 \quad (1)$$

where H_0 is the integrable part, H_1 is the non-integrable perturbation, (J,θ) is a countable set of action and angle coordinates, and ε controls the distance from the integrable limit. For $\varepsilon \neq 0$, the actions J_n are no longer constant but fluctuate around their microcanonical average j, and the non-integrable term H_1 links their time-dynamics defining a coupling network. We distinguish networks which couple all with all (Long Range Network - **LRN**) from those which couple only a finite number of neighboring actions (Short Range Network - **SRN**) and focus on the promising latter ones, which are achieved both in the large energy and weak coupling limits of DNLS, JJ, and KG. Long-lasting breather-like excitations of thermalized many-body systems can be in principle detected using generalized Poincaré manifolds of the phase space defined via the statistical average f of any observable $F(t)$ [4]. The manifold segments the trajectory into consecutive excursions marked by piercing times t_n^i at which $F(t) = f$. We compute the *excursion times* $\tau_n^{\pm}(i) = t_n^{i+1} - t_n^i$ during which $F(t) > f$ (τ_n^+) and $F(t) < f$ (τ_n^-). The specific choice of the set of observables $J_n(t)$ allowed us to perform this detection efficiently for any number of degrees of freedom [5–7]. In Fig.1(a) we show one τ^+ event for the KG case.

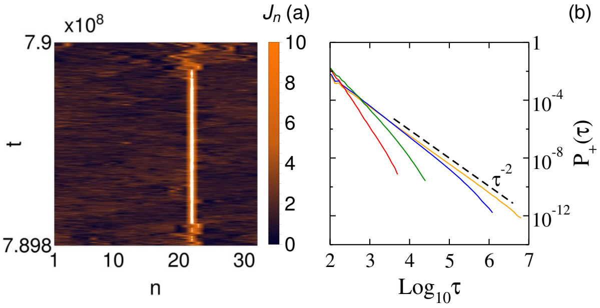

Figure 1: (a) Examples of an excursion time τ^+. (b) Distributions P_+ in the large energy limit of the KG [4, 7].

Such events typically have asymmetric distributions $P_+ \neq P_-$, and while approaching an integrable limit both $P_\pm$ increase their tail weights, with P_+ dominating over P_-. In the SRN case of the JJ [6] and the KG [7] P_+ develops $1/\tau^2$ (Fig.1(b)) close to the integrable limit. We compute the first moment μ_τ and the variance σ_τ of P_+. In the JJ integrable limit of large energy densities both μ_τ and σ_τ but also σ_τ/μ_τ diverge as shown in Fig.2. To link these various time scales to the ergodization time scale, we consider finite time averages $\overline{J}_{n,T} = \frac{1}{T}\int_0^T J_n(t)dt$ of the observables $J_n(t)$. Their distribution $\rho(\overline{J};T)$ yields a first moment $\mu_J(T)$ and a variance $\sigma_J(T)$. If ergodicity holds, it follows that $\mu_J(T\to\infty) = j$ and $\sigma_J(T\to\infty) = 0$ since $\rho(\overline{J};T\to\infty) = \delta(\overline{J} - j)$. We quantify this ergodization process with the dimensionless fluctuation index $q(T) = \frac{\sigma_J^2(T)}{\mu_J^2(T)}$.

That yields the ergodization time scale T_E defined as $q(T \ll T_E) = q(0)$ and $q(T \gg T_E) \sim T_E/T$ (JJ, green squares in Fig.2).

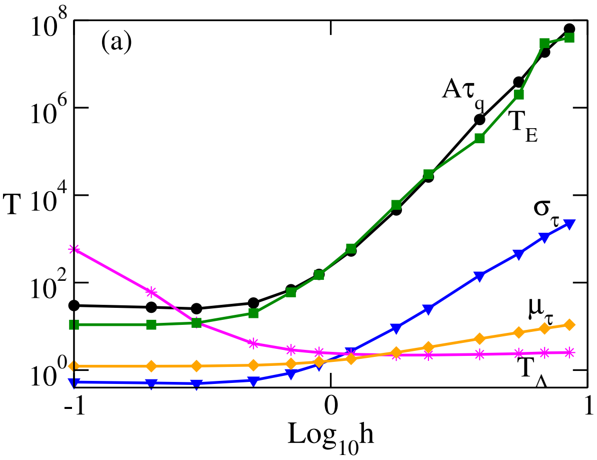

Figure 2: Time scales T_E (green squares), $A\tau_q$ (black circles), T_Λ (magenta stars), μ_τ (orange diamonds) and σ_τ (blue triangles) vs the energy density $h = H/N$ in the JJ network [6].

The loop between event statistics and finite time average distribution properties is closed by neglecting correlations between subsequent events. That assumption yields [6, 7]:

$$T_E \sim \tau_q \equiv \frac{\sigma_\tau^2}{\mu_\tau}. \qquad (2)$$

Eq.(2) is visualized in Fig.2, where $A\tau_q$ is shown with black circles and a fitting parameter $A = 130$. We find excellent agreement of the two independent methods to measure T_E. Now we compare the divergence of T_E with the Lyapunov time T_Λ which is the inverse of the largest Lyapunov exponent Λ (shown in Fig.2 with magenta stars). T_Λ serves as lower bound for the ergodization time. The surprising relation $T_\Lambda \lesssim \mu_\tau$ reveal an uncorrelated growth of the two time scales T_E and T_Λ, reaching an astonishing ratio $T_E/T_\Lambda \geq 10^8$ at $h \approx 10$. These features characterize a novel *dynamical glass* [6, 7]. The dynamical glass is induced by the SRN of actions. In such networks, close to integrability, ergodization is slowed down due to the slow diffusion of rare chaotic regions of resonantly interacting actions. This process is absent in the case of LRN of actions, as for example in the small energy limit of the KG where we found that $T_\Lambda \approx \sigma_\tau$ with T_Λ setting the ergodization time T_E [7]. Our findings let us conjecture that the dynamical glass occurs if the non-integrable term H_1 in Eq.(1) defines a SRN between the observables J_n [6, 7]. The SRN limit and the slow meandering of chaotic spots is observed in the DNLS case as well. However, the DNLS conserves two integrals of motion - energy and norm (particle number). The consequence is that a non-Gibbs phase appears in the density control parameter space [8]. In that non-Gibbs phase, the meandering of chaotic spots is further slowed down to anomalously large times [5], eventually preventing ergodization altogether. The verification of these conjectures require the developing of a quantitative theory. This theory may also clarify the relation between the dynamical glass of a weakly nonintegrable interacting many-body system, the KAM regime of finite systems for which the Kolmogorov-Arnold-Moser theory does apply. Further we expect that the dynamical glass is a primer in searching for many-body localization of corresponding interacting quantum many-body models.

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2.2 Discrete time quantum walks

I. Vakulchyk, M.V. Fistul, S. Flach

Discrete time quantum walks (**DTQW**) were introduced in 1993 as a generalization of classical random walks [1]. They have multiple particularities due to quantum interference which are absent in the classical case. The concept was heavily developed by the quantum computing community in order to implement a variety of quantum logical elements and protocols. From a mathematical perspective DTQWs are unitary maps of wave functions describing the evolution of interacting spinful states on a lattice. From a physics perspective DTQWs are highly efficient unitary map toolboxes to model condensed matter dynamics of interacting many body spinful quantum systems. We considered DTQWs as one-dimensional chains of spin-1/2 states with periodic boundary conditions. The DTQW evolves due to the consecutive acting of quantum coin products and a shift. The map is processing a two-component wave function, $\hat{\psi}_n(t) = \{\psi_{+,n}, \psi_{-,n}\}$ at integer times t and lattice sites n as $\hat{\psi}_n(t+1) = \hat{M}_+\hat{\psi}_{n-1}(t) + \hat{M}_-\hat{\psi}_{n+1}(t)$, and relates to an eigenvalue problem $\hat{\psi}_n(t+1) \equiv \mathrm{e}^{-i\omega}\hat{\psi}_n(t)$.

The matrices $\hat{M}$ are set by quantum coins at a chain site n, with each coin being a four-parameter family of unitary 2×2 matrices

$$\hat{U} = e^{i\varphi}\begin{pmatrix} e^{i\varphi_1}\cos\theta & e^{i\varphi_2}\sin\theta \\ -e^{-i\varphi_2}\sin\theta & e^{-i\varphi_1}\cos\theta \end{pmatrix}.$$

The angles φ, θ, φ_1 and φ_2 correspond to potential and kinetic energy, and external and internal synthetic flux respectively [2]. The shift operator transports all $+1/2$ spin components clockwise and all $-1/2$ components anticlockwise (see Fig.1).

In the absence of disorder, all coin operators are identical. Using Bloch's theorem and a plane wave ansatz with wave number k, the eigenvalue problem solves as $\cos(\omega-\varphi) = \cos\theta\cos(k-\varphi_1)$ [2]. The spectrum consists of two gapped bands with the gap controlled by θ. For the relativistic limit $\theta = 0$ the gap closes and group velocities have k-independent absolute values. For the opposite case $\theta = \pi/2$ both bands turn flat. Our studies were dedicated to different manifestations of disordered and nonlinear dynamics in DTQW.

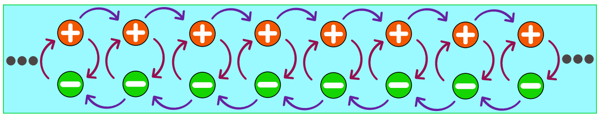

Figure 1: A schematic representation of a general discrete-time quantum walk. Horizontal arrows indicate action of the shift operator. Vertical arrows indicate coin transformations.

In Ref. [2] we considered generalized disordered coins. We studied the separate impact of random uniform uncorrelated distribution in each of the angles. Similarly to the tight-binding model, such disorder leads to exponential Anderson localization [3] of the eigenstates such that $|\Psi_n| \sim e^{-n/\xi}$, where ξ is a characteristic localization length. We used the transfer matrix approach $\Psi_{n+1} = \hat{T}_n\Psi_n$, where $\hat{T}_n$ is the transfer matrix. The localization length follows as $\xi = N/\sum_{n=1}^{N}\ln(|\Psi_n|)$, where N is the system size. We found a novel localization regime for either the potential angle φ or the internal synthetic flux angle φ_2 being strongly disordered such that their respective values are equiprobably distributed on their entire compact support $[0,2\pi]$. The localization length can be computed analytically for all states as [2]

$$\xi = 1/|\ln(|\cos\theta|)| \qquad (1)$$

and can be surprisingly tuned through its entire range $[0,\infty]$ by varying the kinetic energy angle θ. In the limit $\xi(\theta\to 0)\to\infty$ the corresponding Anderson eigenfunctions keep their randomness and do not restore translational invariance, opposite to the known case of weak disorder. The eigenvalues ω fill their compact support $[0,2\pi]$ dense. This limit is therefore of great interest for testing the impact of few and many particle interactions on this novel type of weak Anderson localization.

We considered many-body interactions with a mean field approach and considered nonlinear quantum coins as $\varphi_n = \varphi_n^{(r)} + g|\Psi_n|^2$, where g is the nonlinearity strength [4]. Our goal was to follow the subdiffusive spreading of a wave packet which destroys Anderson localization and spreads way beyond the limits set by the linear theory. Such spreading was studied controversially in Hamiltonian dynamics, with no halt or slowing down observed up to the largest simulation times $t_{max} \sim 10^{8-9}$. With DTQWs we expected to beat previous records by several orders of magnitude. This is possible because DTQWs process the lattice hopping with shift operators which are of nearest neighbour coupling type and actually simply register shifts.

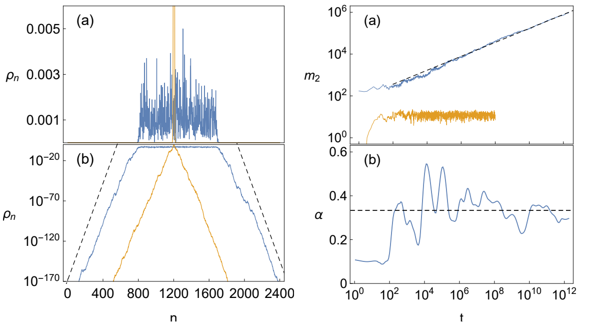

Figure 2: Left plots: wave packet density profiles for linear $g = 0$ (orange solid lines) and nonlinear $g = 3$ (blue solid lines) DTQWs at $t_f = 2 \times 10^{12}$. Black dashed lines: $\mathrm{e}^{-2|n-n_0|/\xi}$. Right plots: (a) $m_2(t)$ for $g = 0$ and $g = 3$ case from left plots. (b) $\alpha(t)$. Black dashed line: $\alpha = 1/3$.

Using single site initial excitations and a GPU cluster with 16,000 cores, we reached $2 \cdot 10^{12}$ characteristic simulation times [4]. We confirmed persistence of subdiffusion, $m_2 \sim t^\alpha$, where m_2 is the second moment of the wavepacket and α is the subdiffusion exponent, see Fig.2.

When nonlinearity is added to the kinetic energy angle in proximity of the flat band case as $\theta = \pi/2 + \lambda|\Psi_n|^2$, $\lambda = 0$ will reduce to the linear case which prohibits any transport. Therefore any transport is solely due to nonzero λ values. We initialized localized wave packets and observed travelling localized solitary excitations [5], see arrow in the left plot in Fig.3.

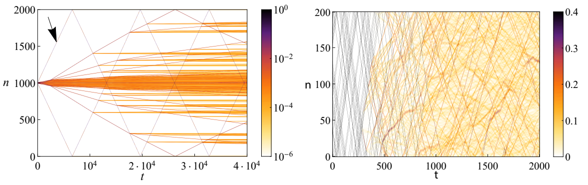

Figure 3: Left plot: typical temporal and spatial pattern of the nonlinear DTQW dynamics and $\lambda = 0.1$. Norm density $|\Psi_n|^2$ is plotted versus time and space with color coding on a logarithmic scale. Black arrow points to one of the moving solitons. Right plot: Evolution of a bullet gas norm density with randomly chosen initial coordinates and phases. The gas is close to an integrable one up to $t \approx 500$ and chaotic and thermalized beyond these times.

These ballistically moving solitary excitations are exact solutions to the DTQW equations [5] and superexponentially localized in space as $|\Psi_n| \sim e^{-e^n}$, and part of a family of moving solitary excitations parametrized by their velocity v. In the relativistic limit $v = 1$ the moving excitations turn into completely compact bullets in space. Two bullets approaching each other will elastically scatter when spaced by even distance, and exchanging their internal state phase. For odd distance spacing bullets do not interact. The evolution of such a gas of left and right moving bullets is shown in Fig.3. The dynamics of the gas will lead to instabilities in the presence of a small noisy background.

Our studies opened a number of interesting research venues using DTQW as a powerful and useful unitary map toolbox.

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2.3 Flatband generation and neccesary and sufficient conditions for flatbands

W. Maimaiti, L.A. Toikka, A. Andreanov,
H.C. Park, O. Gendelman, S. Flach

Flat band (FB) networks are tight-binding translationally invariant lattices which ensure the existence of one or several completely dispersionless bands in the spectrum [1]. FBs have been identified and studied in a number of lattice models in one-, tow- and three-dimensional settings [2], and recently realized experimentally with photonic waveguide networks, and ultracold atomic condensates.

In general FB networks rely on destructive interference rather than a symmetry. The interference is responsible for the existence of compact localized states (CLS): exact FB eigenstates with strictly zero support outside a finite region of the lattice, spanning several unit cells. The entire CLS set is generated by lattice translations. This set can be orthogonal or non-orthogonal, but still forms a complete basis for the FB Hilbert space (in $d = 1$). The presence of a FB signals macroscopic degeneracy and diverging density of states of a corresponding Hamiltonian. Smallest perturbations of such a system will in general lift the degeneracy, leading to uniquely defined eigenstates. Emergent transport properties, in turn, are defined by the type of perturbation. The zero width of the FB calls for non-perturbative effects of the weakest perturbations like disorder or many-body interactions. Thus FB models are high-symmetry cases in a general control parameter space of perturbed lattice Hamiltonians, at which qualitatively different physical phases of matter meet, similar to quantum phase transition points. Examples of such nontrivial and abrupt changes of the wavefunction properties of perturbed FB systems are the appearance of flatband ferromagnetism for many-body interacting fermions, energy dependent scaling of disorder-induced localization length, and Landau-Zener Bloch oscillations in the presence of external fields.

Several approaches to construct FB networks have been proposed: line graphs, local cell construction, "*Origami rules*" in decorated lattices, local symmetries, and repetitions of mini-arrays. None of them is systematic, and can only be considered as a partial accomplishing of a FB generator lacks. A number of FB models have been identified by intuition or simply accidentally.

A systematic classification of FB is therefore an important open problem. The CLS are classified by the number U of lattice unit cells they occupy and the range of hopping. The first attempt to systematically classify FBs through these properties of CLS was published in [3]. The observation was that for $U = 1$ the CLS set forms an orthogonal complete FB basis, with the possibility to detangle the CLS from the rest of the lattice. The inverse procedure - taking *any* lattice, assigning a set of ν detangled CLS states with energies ϵ_ν to each unit cell of the lattice, and finally performing the inverse entangling procedure of mixing the CLS states with the states from each unit cell - leads to the most general $U = 1$ FB generator for arbitrary lattice dimension, arbitrary number of bands, and arbitrary number of FBs amongst them. However, for all $U > 1$ cases - for various reasons the more interesting and nontrivial ones - the inverse detangling method fails, since CLS states are no longer orthogonal and a different approach is needed. In this work we filled this gap and introduced a systematic way to test and construct flatband Hamiltonians.

We considered a one-dimensional ($d = 1$) translationally invariant lattice with $\nu > 1$ lattice sites per unit cell n and the wave function $\Psi = (..., \vec{\psi}_{n-1}, \vec{\psi}_n, ...)$, where the individual vectors $\vec{\psi}_n$ have elements ψ_{nm}, and $m = 1, ..., \nu$ labels the sites inside the unit cell. The time-independent Schrödinger equation on such a network is given by

$$\sum_{m=-\infty}^{\infty} H_m \vec{\psi}_{n+m} = E\vec{\psi}_n \ , \qquad (1)$$

where $\mathcal{H}$ is the Hamiltonian matrix of the network, and E is the eigenenergy. Discrete translational invariance assumes that $\mathcal{H}$ is invariant under shifts $n \rightarrow n + p$. where the $\nu \times \nu$ matrices $H_m = H^{\dagger}_{-m}$ describe the hopping (tunneling) between sites from unit cells at distance m. Note that H_0 (intracell connectivities) is Hermitian, while H_m (intercell connectivities) with $m \neq 0$ are not in general. We further classify networks according to the largest hopping range m_c: $H_m \equiv 0$ for $|m| > m_c \geq 1$.

To test or construct CLS of class U we consider the eigenproblem for:

$$\mathcal{H}_U = \begin{pmatrix} H_0 & H_1 & H_2 & H_3 & \ldots & H_U \\ H_1^{\dagger} & H_0 & H_1 & H_2 & \ldots & H_{U-1} \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & & & & & \vdots \\ H_{U-1}^{\dagger} & \ldots & H_2^{\dagger} & H_1^{\dagger} & H_0 & H_1 \\ H_U^{\dagger} & \ldots & H_3^{\dagger} & H_2^{\dagger} & H_1^{\dagger} & H_0 \end{pmatrix} \qquad (2)$$

with an eigenvector $(\vec{\psi}_1, \vec{\psi}_2, \ldots, \vec{\psi}_U)$ with eigenvalue E_{FB} such that

$$\sum_{m=-m_c}^{m_c} H_m \vec{\psi}_{p+m} = 0 \ , \ \vec{\psi}_{l\leq 0} = \vec{\psi}_{l>U} = 0 \qquad (3)$$

for all integers p with $-m_c + 1 \leq p \leq 0$ and $U + 1 \leq p \leq U + m_c$. Similar equations hold for $H_m^{\dagger}$. These two sets of equations ensure $\vec{\psi}_{l\leq 0} = \vec{\psi}_{l>U} = 0$. Then the Hamiltonian has a FB of class U. Given a network Hamiltonian, and successively increasing the test value for $U = 1, 2, ...$ we arrive at a systematic procedure to identify a FB model with finite class U.

Inverting the above sufficient tester algorithm allows to arrive at a systematic local FB generator based on CLS properties. The H_m becomes the variables that we want to fix by solving (2-3). The problem then reduces to appropriate parameterization of H_m, $m > 0$.

As an application of our method we described the most generic FB generator for $U = 2$, $m_c = 1$ in one dimension: since (3) enforce H_1 to have a zero mode, it turned out convenient to represent H_1 using its spectral decomposition: $H_1 = \alpha|\theta, \delta\rangle\langle\varphi, \gamma|$ as follows:

$$H_1 = \alpha \begin{pmatrix} \cos\theta\cos\varphi & e^{i\gamma}\cos\theta\sin\varphi \\ e^{-i\delta}\sin\theta\cos\varphi & e^{-i(\delta-\gamma)}\sin\theta\sin\varphi \end{pmatrix} , \qquad (4)$$

Solving (2-3), we have found that FB exist for any phases $\gamma = \delta$, specific values of $|\alpha|(\theta, \phi)$ and θ, ϕ. Importantly, though the FB hoppings are fined-tuned, they form a continuous manifold in the space of hopping matrices H_1.

This construction extends to larger values of ν and m_c as we demonstrated in a consequent work, the main challenge being to identify the correct parametrization of the hopping matrices H_m.

It is also possible to identify the FB starting from the complimentary Bloch representation of the Hamiltonian rather then the real space based CLS approach discussed above. Indeed the generic Hamiltonian (1) can be rewritten as

$$\mathcal{H}_q = \sum_{m=1}^{M} \left\{ e^{i\mathbf{q}\cdot\mathbf{R}_m} H_m^{\dagger} + e^{-i\mathbf{q}\cdot\mathbf{R}_m} H_m \right\} + H_0, \qquad (5)$$

Then existence of a flartband in the spectrum is equivalent to the following equation

$$\det\left(\mathcal{H}_q - E_{\mathrm{FB}}\mathbb{I}\right) = 0, \qquad \forall q, \qquad (6)$$

that can be written as ($\eta = e^{iq}$)

$$\frac{\tilde{x}_{-1}}{2} + \frac{1}{\eta}\tilde{x}_{-2} + \frac{1}{\eta^2}\tilde{x}_{-3} + \ldots + \frac{1}{\eta^N}\tilde{x}_{-(N+1)} = 0. \qquad (7)$$

thanks to the determinant (6) being a characteristic polynomial of $\mathcal{H}_q$. The above equations implies a set of coupled polynomial equations on the coefficients of the hopping matrices H_m. The case of generic H_m is not sovlable, however for specific lattices, thanks to sparsity of H_m reflecting the connectivity of the lattice, these equations become solvable.

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2.4 Chiral flat bands: Existence, engineering and stability

A. Ramachandran, A. Andreanov, S. Flach

Hermitian tight binding translationally invariant lattices with the eigenvalue problem $E\Psi_l = -\sum_m t_{lm}\Psi_m$ and certain local symmetries have been shown to sustain one or a few completely dispersionless bands, called flat bands (FB) in their band structure. [1] The interest in FBs is due to the macrscopic degeneracy they host, which is lifted by almost any perturbation and leading to interesting new physics: groundstate ferromagnetism, unconventional localization, Landau-Zener Bloch oscillations, to name a few examples. Flat bands with finite range hoppings rely on the existence of a macroscopic number of degenerate compact localized eigenstates (CLS) at the FB energy E_{FB} which have strictly zero amplitudes outside a finite region of the lattice due to destructive interference. Flat band networks have been proposed in one, two, and three dimensions and various flat band generators were identified, which harvest on local symmetries. A recent systematic attempt to classify flat band networks through the properties of CLS was used to obtain a systematic flat band network generator for one-dimensional two-band and higher networks. Experimental observations of FBs and CLS are reported in photonic waveguide networks, exciton-polariton condensates, and ultracold atomic condensates. FBs are obtained through a proper fine-tuning of the network parameters. For experimental realizations, the understanding and usage of FB protecting symmetries is therefore of high priority.

The interplay of flat bands (or equivalently CLS) and additional symmetries was discussed in few publications so far. The importance of chiral symmetry for zero energy flatbands was discussed in several works: Non-gapped flat band in dice lattice model as a consequence of the underlying lattice symmetry was reported by Sutherland, as well as possible generalizations. Bound states in continuum protected by chiral symmetry of the lattice with flatbands, were studied by Mur-Petit et. al. Poli et. al. examined effect of partial breaking of chiral symmetry in a two-dimensional Lieb lattice, which destroyed the flat band. Leykam et. al. studied one-dimensional diamond chain with onsite disorder which breaks chiral symmetry, and observed a finite localization length for states at the flatband energy, as opposed to strict compact localization in the case of preserved chiral symmetry. Green et. al. speculated that time-reversal symmetry has to be broken to gap away the flat band, which might be relevant in presence of interactions. Read analyzed the existence of CLS and, therefore, flatbands, and their relation to general topological properties for generic Hamiltonians belonging to the ten symmetry classes using algebraic K-theory.

Bipartite lattices separate into two A, B sublattices such that $E\Psi_l^{A,B} = -\sum_m t_{lm}\Psi_m^{B,A}$ and possess *chiral symmetry* (CS): if $\{\Psi^A, \Psi^B\}$ is an eigenvector to eigenenergy E, then $\{\mp\Psi^A, \pm\Psi^B\}$ is an eigenvector to eigenenergy $-E$. We studied chiral flat bands (CFB) with $E_{FB} = 0$ in such systems, and the ways the chiral symmetry is protecting them. Lieb theorem implies that chiral lattices with an odd number of bands always possess at least one chiral flat band, and we present a general method to compute the total number of CFBs. This allows us to derive a simple CFB network generating principle in various lattice dimensions. Disorder (or other perturbations) which preserve CS also preserve the CFB, and we show that CLS survive up to modifications. CFBs are generically gapped away from other spectral parts, however, the gap is replaced by a pseudogap in case of hopping disorder due to Griffiths effects.

A well-known theorem states the existence of zero-energy states for bipartite lattices: If the number N_A of the majority A-sublattice sites is larger than the corresponding number N_B of the minority B-sublattice, then there are at least $\Delta N = |N_A - N_B|$ states $\{\Psi^A, 0\}$ at energy $E = 0$, which occupy the majority sublattice only.

These results naturally lead to the systematic classification of chiral flatbands: Consider a translationally invariant d-dimensional bipartite lattice, odd number ν of sites per unit cells and $1 \leq \mu_B < \mu_A < \nu$. The μ_A A-sites in any unit cell are only connected with non-zero hopping terms t_{lm} to the remaining μ_B B-sites (possibly belonging to other unit cells). The general band structure is given by dispersion relations $E_\mu(\vec{k})$ with the band index $\mu = 1, ..., \nu$ and $\vec{k}$ a d-component Bloch vector scanning the Brillouin zone. It follows already by general CS that at least one of the bands must either cross $E = 0$ (finite number of zero energy states) or be a FB at $E = 0$ (macroscopic number of zero energy states), since any band which does not cross $E = 0$ is either positive or negative valued, and has a symmetry related partner band. Due to the odd number of bands, there is at least one *unpaired* band which therefore must transform into itself under CS action. In the following we focus on Hermitian system, but the concepts can be carried over to non-Hermitian systems as well. Further, since ν is odd, the difference in the number of sites on the A and B sublattices $\Delta N = N_{uc}(2\mu_A - \nu) \neq 0$, where $N_{uc} \sim L^d$ is the number of unit cells, and L is the linear dimension. This implies a macroscopic degeneracy at $E = 0$, which is only possible with precisely $(2\mu_A - \nu)$ FBs at $E = 0$. This observation suggests a natural classification of CFB by the imbalance of minority and majority sites, and canl be used for a CFB generator: By fixing the space dimension and the Bravais lattice, and looping over the number of sites ν and the number of sites of the majority sublattice μ_A as well as the hopping range, one can systematically explore all the possible chiral flatband models. The results of application of this classification in $d = 1, 2$ and $\nu \leq 5$ are presented in Fig. 1.

We have also studied the effect of the chiral symmetry in presence of perturbations and demonstrated that conical intersections of FB appearing in chiral Hamiltonians are in general accidental and are removed by generic perturbations preserving the FB. This disproves the argument of Green, that time-reversal symmetry breaking might be needed to gap away chiral flatbands. Also disorder that respects chiral symmetry, i.e. hopping disorder, does not lift the degeneracy of the chiral flatband.

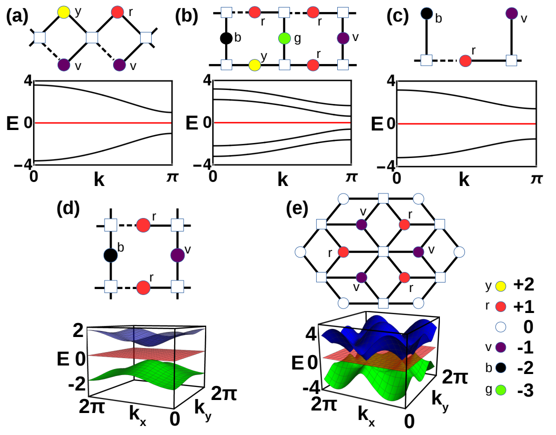

FIG. 1. (Color online) Modifications of known CFB networks and their band structure (see e.g. 1 and 6). Majority and minority sublattice sites are shown with circles and squares respectively. Solid lines: $t = 1$, dashed lines: $t = 2$. CLS amplitudes (not normalized) are shown in color code. (a) diamond, (b) 1d Lieb, (c) stub (d) 2d Lieb, (e) $\mathcal{T}_3$ (dice).

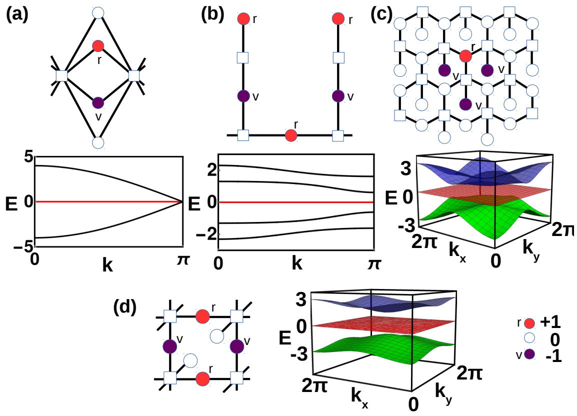

FIG. 2. (Color online) Novel CFB examples (with dispersion relations). Majority and minority sublattice sites are shown with circles and squares respectively. CLS amplitudes (not normalized) are shown in color code. (a) double diamond, (b) stub3, (c) 2d stub (d) decorated Lieb

Figure 1

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2.5 Conductance oscillations in Chern insulator junctions: Valley-isospin dependence and Aharonov-Bohm effects

N. Myoung, H.C. Park

Graphene is a promising material for studying quantum Hall effects with gate-tunable filling factors on account of its capability for controlling charge density via field effects. Studies involving conductance measurements through graphene under a homogeneous magnetic field report non-integer conductance plateaus for gate-tunable bipolar junctions. The topological nature of the quantum Hall system has been clearly understood via the presence of gapless edge states that are topologically protected. Bulk-boundary correspondence offers an intuitive way of understanding the properties of these edge states: the number of conducting channels is characterized by the topological invariant of the quantum Hall insulator. It has been well known that the topological invariant (or so-called Chern number) of a quantum Hall insulator is given by the filling factor in the integer quantum Hall effect.

The observation of non-integer conductance plateaus in bipolar graphene quantum Hall systems has been interpreted by the equilibration of interface states at the p-n junction, with theoretical efforts supporting experimental findings by considering edge and interface disorders. Junction conductance via interface equilibration has also been reported for p-n-p junctions in quantum Hall graphene systems, with the consideration that there can be reflections at the bipolar junction. These studies were carried out in macroscopic systems where mesoscopic fluctuations were ignored. However, T. Low has shown that observed junction conductance in ballistic systems is distinct from disordered ones, via crossover between the coherent and Ohmic regimes. Mesoscopic conductance fluctuation should therefore be expected to appear in the coherent regime, e.g., a valley-isospin dependence of the quantum Hall effects in graphene p-n junctions.

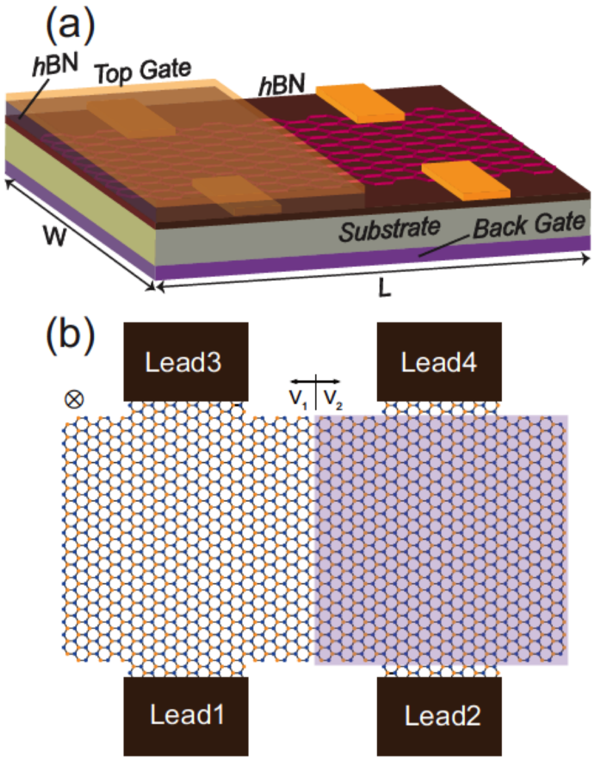

Figure 1: Schematic figure we considered.

In this work, we show that mesoscopic consequences in the conductance across a Chern insulator junction can be observed even in the presence of edge disorders, when both regions of the Chern insulator junction are on the second Hall plateaus [1]. As the length of the junction interface varies, we reveal that the conductance across the junction exhibits atomic-scale period fluctuation and long-period oscillation according to the Chern number configuration. While this fluctuation, associated with valley-isospin dependence, can be eliminated by the presence of edge roughness, the long-range conductance oscillation survives despite a randomly distributed edge roughness. We demonstrate that the conductance oscillation originates from an Aharonov-Bohm (AB) interferometry implicitly contained in the Chern insulator junction; since the metallic channels around the interface are spatially separated, they effectively create an area enclosing magnetic flux. The AB conductance oscillation also exhibits a beating pattern with a very long period, reflecting the multi-path interferometry of the implicit AB ring. Finally, we discover a gate-tunable visibility of the AB oscillation and further show that a suppression of the AB conductance oscillation can be achieved through gate control.

In terms of topology, quantum Hall states have been revealed to have topological characteristics and can regarded as Chern insulator. Since Chern numbers of quantum Hall states in graphene are tunable by electric-field effect, a heterojunction of different Chern insulators is expected to be realized by using the bipolar junction of graphene in the quantum Hall regime. Such a device structure is feasible to fabricate with gated structures under a homogeneous magnetic field. Let us note that there should be a thin dielectric layer (e.g. few-layer h-BN) between graphene and the top gate electrode, although we omit it here for simplicity. With an analytical approach, the effective Dirac Hamiltonian for graphene under a homogeneous magnetic field reads

$$H = \hbar v_F \vec{\sigma} \cdot \vec{\pi} + V(x)\,, \tag{1}$$

where $v_F \simeq 10^6\ \mathrm{ms}^{-1}$ is the Fermi velocity of graphene, $\vec{\sigma} = (\sigma_1, \sigma_2)$ are the Pauli matrices, $\vec{\pi} = \vec{p} + e\vec{A}$, and the electrostatic potential is given as either a sign function or hyperbolic tangent function:

$$V(x) = V_0 \tanh\left(\frac{x}{\xi}\right), \tag{2a}$$

where $V_0 = V_2 = -V_1$; V_1 and V_2 are potential energies in the left and right sides of the p-n junction as shown in Fig. 1.

Our results provide possible guides to experimental confirmation of the mesoscpic transport phenomena in quantum Hall graphene with a p-n junction. Especially, the valley-isospin dependence of the conductance through the p-n junction in quantum Hall graphene can be observed if the edges of graphene sample are perfectly clean. On the other hand, the conductance oscillation due to intrinsic Aharonov-Bohm interferometry can be measured when the p-n junction is sufficiently sharp as shown in Fig. 2. By examining the suppression of the AB oscillations, required sharpness of the junction is about ≤4.2 nm for a given magnetic field strength of 30 T, which seems to be feasible at present or in near future. Moreover, lower junction sharpness may be required for lower magnetic fields, since the enclosed area by the interface channels effectively increases as magnetic field decreases.

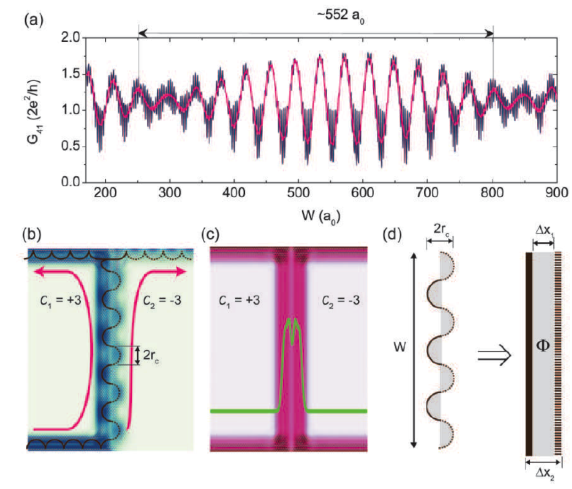

Figure 2: (a) Beat of the conductance across the junction for given potential $V_0 = \left(\sqrt{2}+1\right)E_0/2$ as a function of W. The beat period W_{beat} is found to be $\sim 552a_0$. (b) Probability density map at $E_F = 0$ for an incoming mode from the left of the bottom edge, with illustrations of the pathway of the metallic channels and the corresponding semi-classical skipping motions. (c) Local density of states map corresponding to (b). (d) Schematics of the implicit AB interferometry. Left panel: A skipping motion along the W-long interface encloses an area through which magnetic fluxes penetrate. Right panel: An effective interferometry encloses the same area as that enclosed by the skipping motion, through which magnetic flux Φ penetrates in total. Both pathways are regarded as finite-width arms of the AB interferometry, characterized by the outer and inner distances $\Delta x_{1,2}$.

[1] Nojoon Myoung and Hee Chul Park, Conductance oscillations in Chern insulator junctions: Valley-isospin dependence and Aharonov-Bohm effects, Phys. Rev. B 96, 235435 (2017)

2.6 Strong two-mode parametric interaction and amplification in a nanomechanical resonator

S. Cho, S.U. Cho, M. Jo, J. Suh, H.C. Park,
S.G. Kim, S.-B. Shim,Y.D. Park

Nanomechanical systems have attracted research interests from diverse scientific and engineering fields as they exhibit unique characteristics, such as versatile coupling to different physical systems, high sensitivity to external forces, compatibility with conventional electronics and semiconductor processes, and low-power operation. Recently, these potentials have been realized in ultra-sensitive mass spectroscopy, quantum-limited force measurements, and coherent quantum converters. While many of these applications require ever smaller and lighter mechanical devices to improve performance, the size of the mechanical system is often incommensurate to the efficiency of the electronic or optical transduction of nanomechanical motion: the coupling between the mechanical resonator and the motion transducer generally diminishes as the system size is reduced.

It has been shown that two resonant oscillators coupled by a time-varying non-linear component can become a non-degenerate parametric amplifier in both electrical and optical domains. In the mechanical domain, application of the sum frequency of different resonant modes has shown an enhancement of resonantly driven mechanical motions in a torsional structure. Despite these possibilities of developing a mechanical non-degenerate amplifier, the detailed mechanism based on their structure and flexural motion is not fully understood.

Our work presents a novel idea to apply the non-degenerate mechanical amplification technique to a single nanomechanical structure with multiple resonant modes. The technique utilizes coupling between different flexural modes in mechanical resonators via mechanical motion itself; more specifically, our method is based on the dielectric gradient force transduction scheme as shown in Fig. 1.

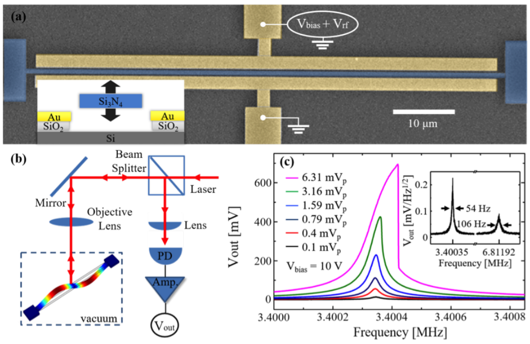

Figure 1: Description of the nanoelectromechanical resonator and optical measurement scheme. (a) The doubly-clamped beam (blue) is in thermal motion, and an RF-signal (resonant or parametric pump) in combination with DC bias is applied via metal electrodes (yellow). The parametric pump is tuned to the frequency of the difference (red-detuned) or the sum (blue-detuned) of the frequency of its 1st and 2nd flexural modes. The inset depicts a schematic diagram of the cross-sectional geometry of the nanomechanical device. (b) Schematic diagram of optical measurement based on amplitude modulation from the surface of the nanomechanical structure.(c) Driven and thermal motion of the nanomechanical resonator. With a strong resonant driving signal (V_{rf}) near its resonant frequency, the nanomechanical resonator presents a clear nonlinear response.

By modulating the electric field acting on a dielectric nanobeam (or pump) at the difference between the resonance frequencies of two independent modes, we observe parametric coupling between two nanomechanical modes in thermal motion. When the pump frequency reaches the sum of the two resonance frequencies, an amplification of thermomechanical motion occurs. At stronger pump amplitude, we observe non-degenerate parametric amplification of thermal motion at two pump frequencies different from the exact sum frequency of the two flexural modes, following a decrease in amplification gain at exact pump frequency. We provide a theoretical treatment from general Euler–Bernoulli equations that explains these complex dynamics thoroughly, suggesting that this coupling and amplification process arises from non-degenerate parametric interactions between two normal modes in the single nanomechanical oscillator. Furthermore, our observation presents that coupling between flexural modes which were expected not to be coupled can become possible due to structural asymmetry. A numerical analysis based on experimental parameters is also provided to support our theoretical model. The coupled equations are as following,

$$\ddot{\chi}_{1,2} + \gamma_{1,2}\dot{\chi}_{1,2} + \omega^2_{1,2}(V_b)\chi_{1,2} + 2\cos(\omega_p t)\sum_{n=1,2}\kappa_{1,2n}\chi_n = 2F_d\cos(\omega_d t), \tag{1a}$$

For the coupled equation of motion, κ_{mn} represents the parametric ($m = n$) and coupling ($m \neq n$) coefficient due to the structural asymmetry between flexural modes of beam. As the nanomechanical resonator is in thermal motion, we include thermal driving force, with the amplitude of F_d only affecting the relative amplitude of the spectral response of the nanomechanical resonator. Here, γ_i and $\omega_i(V_b)$ are the damping rate and resonant frequency of the i-th flexural mode modified by DC bias voltage.

As shown in Fig. 2, we demonstrated parametric mode interaction in the strong coupling regime between two flexural modes of a nanomechanical resonator by modulating the external electric field. With a parametric pump at the red-detuned sideband of the 1st and 2nd modes, both mechanical modes presented a clear normal-mode splitting feature, with a splitting frequency over 230 Hz. Using the same technique with a blue-detuned sideband pump, we realize non-degenerate parametric amplification of thermal motion, with amplification gain reaching 33 (30 dB) and 79 (38 dB) in amplitude for the 1st and 2nd modes, respectively. The nanomechanical resonator also exhibited resonant spectrum splitting by strong parametric pumping. These results demonstrate that parametric dynamics between normal modes can be achieved by modulating external parameters rather than strain-mediated coupling by resonant driving. With potential for active nonlinear devices and mechanical logic devices, coupling based on an external control parameter as shown here can be extended to multiple mechanical modes of distinct devices and coupled hybrid systems. Moreover, non-degenerate parametric amplification can be suitable for various sensing applications considering its advantages in amplifying the motional amplitude of the device as well as high gain in the absence of preliminary phase information.

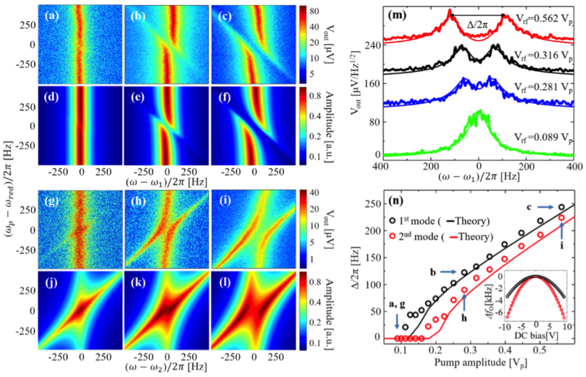

Figure 2: Parametric coupling by red-detuned sideband pump. (a)–(c), (g)–(i) Parametric coupling between 1st and 2nd flexural modes, respectively. Responses of the 1st and 2nd modes of the nanomechanical resonator to a parametric pump near the red-detuned sideband frequency, $\omega_{red} = \omega_2 - \omega_1$, for different pump amplitudes. (d)–(f), (j)–(l) Numerical analysis for the responses of the 1st and 2nd flexural modes, respectively, derived from slowly-varying ω amplitudes of Eqs.(1a). (m) Spectral response of the 1st flexural mode in thermal motion to different parametric pump amplitudes, and the theoretically estimated spectrum of flexural modes. (n) Mode-splitting frequency by applied parametric pump amplitude. The theoretically estimated mode-splitting frequency is shown as a solid line for each mode.

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2.7 Shedding light on topological superconductors

K.H.A. Villegas, V.M. Kovalev, F.V. Kusmartsev, I.G. Savenko

Superconductivity is difficult to characterize with light due to its weak light–matter interaction. To test whether materials are superconductors, electric (resistivity-based) and magnetic (Meissner effect-based) techniques are routinely used. On one hand, electrical conductivity measurements used to study conventional superconductors have proved to be challenging due to the mutual influence of the free electrons associated with the metallic surface and the Cooper pairs of the superconducting bulk. On the other hand, diamagnetic Meissner magnetization measurements require a minimal volume, which is an issue for surface topological superconductivity.

In our work, we proposed an optical approach to monitor the behavior of superconductors. This is done by coupling, via Coulomb interaction, the superconductor layer to a parallel metallic layer as illustrated in Fig. 1a. Using the polarization functions of the 2DEG and superconductor, we solve the eigenvalue problem and find two branches of dispersion of the hybrid modes as shown in Fig. 1b. The interactions and schematic of the polarization diagrams are summarized in Fig. 1c.

Using the linear response theory, we calculated the power absorption when an electromagnetic field is applied on the hybrid. This is done by using the formula

$$\mathcal{P}(\omega) = \frac{1}{2}\left\langle \mathcal{R}e\int d^2r\mathbf{J}(\mathbf{r},t)\cdot\mathbf{E}^*(\mathbf{r},t)\right\rangle.$$

The current $\mathbf{J}$ is monitored in both 2DEG and superconductor layer. The resulting power absorption by the hybrid system is summarized in Fig. 2. We found that these excitations are highly optically active and display strong resonances in optical absorption measurements. The system has a giant hybrid Fano resonance [1, 2], which arises in both normal and superconducting hybrid subsystems due to their mutual influence. The shape and positions of the peaks and the dip of the Fano resonance may uniquely characterize both the superconducting and metallic subsystems. Thus, our findings open a prospective method, being optical and noninvasive, for the characterization and testing of materials for superconductivity.

We also considered the case when the superconductor layer is a topologically non-trivial p-wave type and found that the power absorption still exhibits Fano resonance. This opens the possibility of an alternative optical method for detecting Majorana fermions in topological superconductors, which is analogous to zero-bias anomaly in tunneling spectroscopy [3] but instead uses light interaction. Chen et. al. [4] proposed a similar optical-detection method but using hybrid quantum dot-nanomechanical resonator. In contrasts, in our method, the strong plasmon coupling which produces a giant hybrid resonance should provide a major advantage over the former.

Moreover, the recent discovery of high-temperature light-induced superconductivity in K_2C_{60} [5] has stimulated an activity in the scientific community to test materials with light. Thus, our finding of enhanced light coupling in metal–superconducting hybrids alongside the possibility of testing is expected to open a new direction in this activity, since it creates many opportunities for discoveries of condensed states induced by light.

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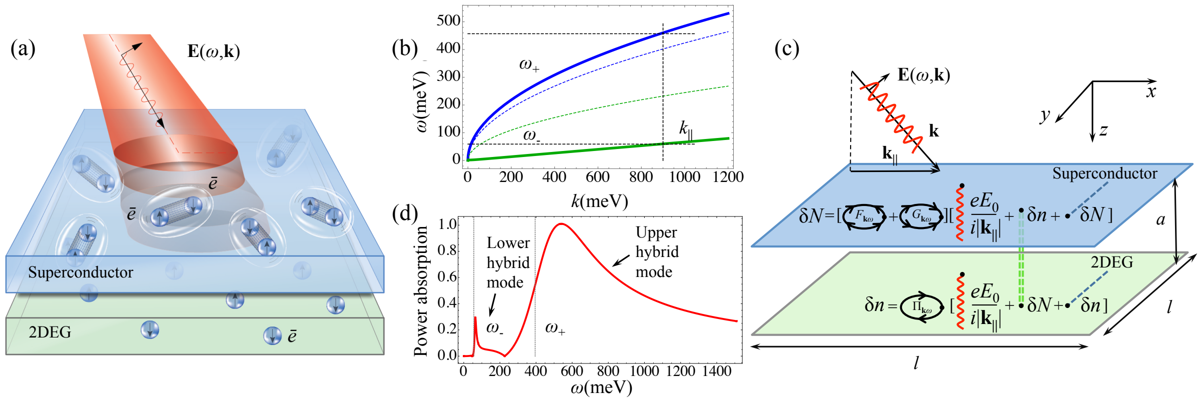

Figure 1: (a) Hybrid normal metal–superconductor structure. (b) Hybrid eigenmodes. (c) Relevant interactions in the system. (d) Fano resonance profile.

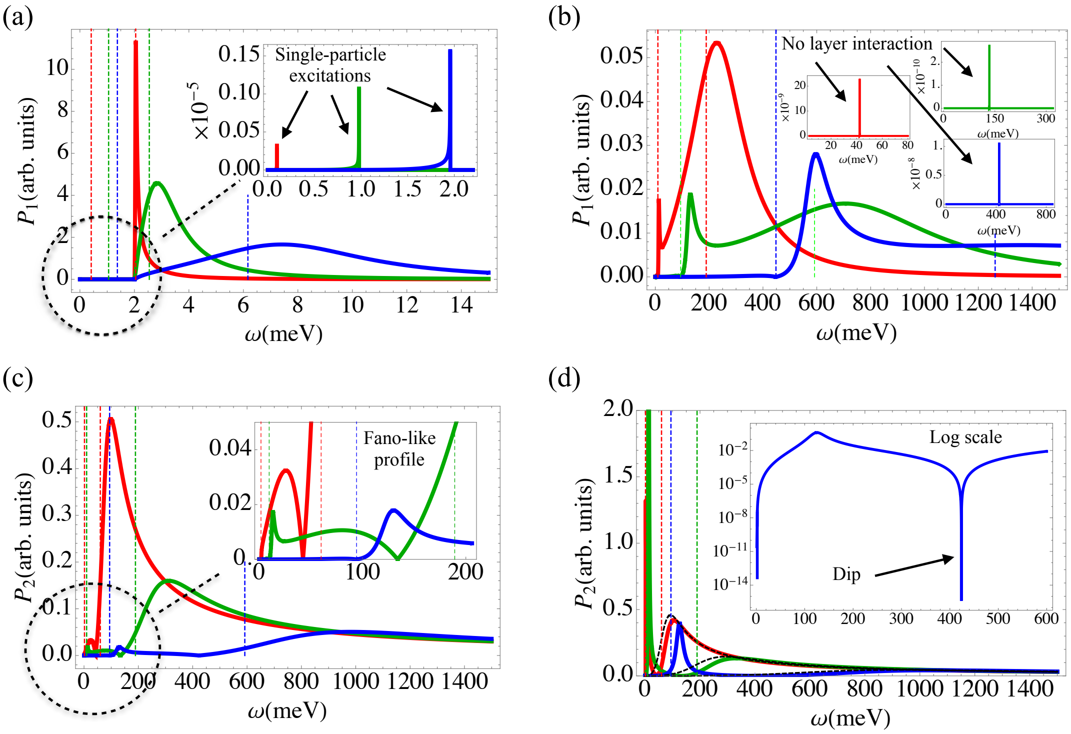

Figure 2: Power absorption monitored in 2DEG ((a) – (b)) and superconductor ((c)–(d)) as a function of ω. Vertical dashed lines show the hybrid mode locations. (a) $k = 1.0 \times 10^{-3}$ (red curve), 1.0×10^{-2} (green curve), and 1.0×10^{-1} meV (blue curve). (b) $k = 1.0 \times 10^{1}$ (red curve), 1.0×10^{2} (green curve), and 1.0×10^{3} meV (blue curve). (c) Both layers are exposed to the EMF. (d) No external field on the normal layer. In (c) and (d), $k = 1.0 \times 10^{1}$ (red curves), 1.0×10^{2} (green curves), 1.0×10^{3} meV (blue curves). Dashed black curves in (d) show the case when interlayer coupling is turned off.

2.8 Multivalley engineering in semiconductor microcavities

M. Sun, I.G. Savenko, H. Flayac, T.C.H. Liew

In this work, we considered the behavior of exciton-polaritons (EPs) in a microcavity where both the optical and excitonic components are separately manipulated by a periodic potential. We showed that such a system supports degenerate ground-states appearing at non-zero in-plane momenta, corresponding to multiple valleys in reciprocal space, which are further separated in polarization corresponding to a polarization-valley coupling in the system.

We start by considering a one-dimensional (1D) system of cavity photons and quantum-well (QW) excitons, which experience potentials with the same periodicity but different alignment in energy, as shown in Fig. 1a.

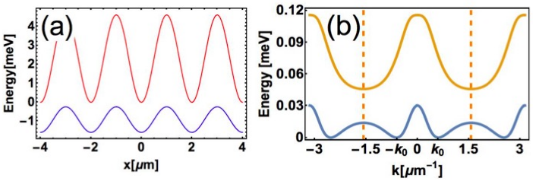

Figure 1: System schematic. (a) Potential profiles for QW excitons (red) and cavity photons (blue). (b) Numerically calculated dispersion of the lowest-energy EPs (blue).

Applying the Bloch theory and the model of coupled harmonic oscillators, we can solve the eigenvalue problem of the system, which in a brief form reads:

$$\begin{pmatrix} \lambda_C - i\hbar/\tau_C - E & \Omega \\ \Omega & \lambda_X - i\hbar/\tau_X - E \end{pmatrix} C_k + \sum_G \begin{pmatrix} \tilde{V}_C(G) & 0 \\ 0 & \tilde{V}_X(G) \end{pmatrix} C_{k-G} = 0, \quad (1)$$

where $\lambda_C = \frac{\hbar^2 k^2}{2m_C}$ and $\lambda_X = \frac{\hbar^2 k^2}{2m_X}$ are the kinetic energy terms of the photonic and excitonic counterparts. Parameters $\tau_{C,X}$ are the lifetimes of the cavity photons and excitons, Ω is the exciton-photon coupling constant, $\tilde{V}_C(G)$ and $\tilde{V}_X(G)$ are the Fourier series coefficients of the potentials localizing the cavity photons and excitons in real space. The summation is over G, which is the reciprocal lattice vector of the periodic potential; C_k are the (vector) amplitudes of the wave functions of polaritons in the photon-exciton basis with various k; E are the eigenenergies of the EP modes. After solution of the eigenvalue problem, we find the dispersion of the system of EPs in k-space shown in Fig. 1b. This dispersion is characterized by two minima at non-zero wave vectors, $k = k_0$. This result is the milestone of this manuscript and in the following we show that this peculiarity leads to non-trivial effects such as spontaneous momentum symmetry breaking upon EP condensation and quantum entanglement.

Let us study the potential consequences of the dispersion shown in Fig. 1b case. We first consider qualitative arguments in the limit of thermal equilibrium. Given the dispersion, E_k, obtained in the linear regime, the Hamiltonian of the system can be written as

$$\hat{\mathcal{H}} = \sum_k E_k \hat{a}_k^\dagger \hat{a}_k + \alpha \hat{a}_k^\dagger \hat{a}_k^\dagger \hat{a}_k \hat{a}_k + 2\alpha \sum_{k' \neq k} \hat{a}_k^\dagger \hat{a}_{k'}^\dagger \hat{a}_k \hat{a}_{k'}, \quad (2)$$

where we introduce polariton-polariton interaction with the strength α. The factor 2 in Eq. (2) is characteristic of the momentum space scattering processes and can be related to inequivalent permutations of $\hat{a}_k^\dagger \hat{a}_{k'}^\dagger \hat{a}_k \hat{a}_{k'}$. At zero temperature, one can expect that only the two lowest energy momentum states at $k_1 = -k_0$ and $k_2 = k_0$ are populated, where k_0 is the momentum of the right minimum of the blue curve in Fig. 1b. Then the energy of the system can be written as

$$E(n_1, n_2) = nE_{k_1} + \alpha \left(n_1^2 + n_2^2 - n + 4n_1 n_2 \right), \quad (3)$$

where we denoted $n_{k_1(k_2)} = n_{1(2)}$ and the total population $n = n_1 + n_2$. The lowest energy state thus appears when $\rho = (n_1 - n_2)/n$ achieves its extreme value of ± 1. In other words, at zero temperature we expect the system to spontaneously choose either the state with all the EPs at k_1 or k_2. This can be further confirmed by calculating the second order correlation function and spectrum corresponding to Hamiltonian 2, as shown in Fig. 2.

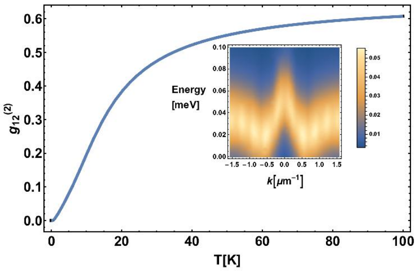

Figure 2: Second-order correlation function as a function of temperature with fixed number of EPs, $n = 100$. Inset picture demonstrates the low-density result compared with the dispersion in Fig. 1b.

Then we consider a more accurate non-equilibrium modeling which consider the finite life time of exciton-polaritons in an InGaAlAs alloy-based microcavity. In Fig. 3a, we switch off the polariton-polariton interaction and see that in this case there is no blueshift and the particles occupy mostly the edge of the Brillouin zone. It happens due to the fact that the lifetime of particles increases with the increase of $|k_{\|}|$ and thus the decay rate decreases with $|k_{\|}|$, see red curve in Fig. 3. However, with account of the interaction, we achieve the degenerate condensation at points $k = \pm k_0$ due to the interplay of particle lifetime and interactions, see Fig. 3b.

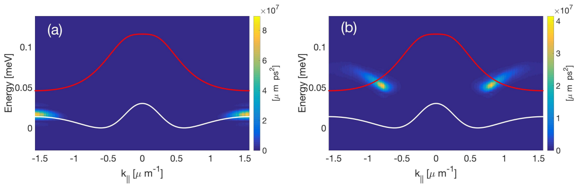

Figure 3: Distribution of EPs in the steady state with account of the acoustic phonon-assisted scattering. Red curves show the k-dependence of the decay rates. White curves show the EP dispersion in the linear regime. The polariton-polariton interaction is switched off (a) and on (b) by putting α zero and non-zero, respectively.

Figure 4a shows the energy of the system ground state in the first Brillouin zone. A fundamental feature of 2D semiconductors for valleytronics is the spin-valley coupling that allows different valleys to be excited with light of different polarization. In the system of EPs, it is well-known that transverse-electric and transverse-magnetic polarized modes are split in energy. This splitting can be modeled by introducing a spin-orbit coupling Hamiltonian acting on the photon spin degree of freedom:

$$\mathcal{H}_{TE-TM} = \begin{pmatrix} 0 & \Delta\left(i\frac{\partial}{\partial x} + \frac{\partial}{\partial y}\right)^2 \\ \Delta\left(i\frac{\partial}{\partial x} - \frac{\partial}{\partial y}\right)^2 & 0 \end{pmatrix}. \tag{4}$$

Accounting for this splitting, we obtain the polarization structure of the lowest energy band shown in Fig. 4b. Here we note that different valleys have different polarizations, which implies that they can be selectively excited by a resonant excitation of specific polarization.

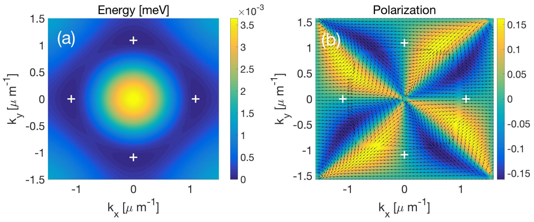

Figure 4: Illustration of the multivalley coupling. (a) the energy dispersion in the First Brillouin zone. (b) polarization chart. The arrows show the polarization in x and y directions, the color represent the polarization in z direction. White crosses correspond to the minima of the energy dispersion.

We have considered the formation of EPs in a semiconductor microcavity with separate spatially patterned potentials for cavity photons and excitons. The different confinement of photons and excitons allows for a momentum dependent coupling which gives rise to a unique form of the dispersion in which degenerate ground states appear at non-zero momenta. In strong relaxation limit, a simple equilibrium theoretical model predicts spontaneous symmetry breaking in momentum space. In weak relaxation limit, a non-equilibrium model accounting for phonon scattering processes shows non-equilibrium condensation at non-zero wave vector.

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2.9 Adaptively truncated Hilbert space based impurity solver for dynamical mean-field theory

A. Go, A.J. Millis

The quantum impurity model describes systems where an *impurity* including a small number of correlated orbitals is embedded in the environment, which is non-correlated but has much more degrees of freedom. Since it was proposed to explain the behavior of dilute magnetic impurity in metallic hosts [1, 2], the impurity models have given great insights on condensed matter physics as reasonable simplifications of reality: the Kondo effect [2], core-level spectroscopy [3], and even in nonequilibrium context, transport through quantum dots [4,5]. The appearance of the DMFT also raised the importance of the impurity solver by establishing self-consistency between a large, intractable problem and a manageable impurity model [6]. Obtaining accurate solution of the impurity model for wide frequency range is therefore vital to understand many correlated systems better.

The DMFT has proven its power by successfully explaining various emergent behaviors in correlated systems [6–8]. However, the DMFT has not reached its full potential due to the imperfection of existing impurity solvers. Specifically, multi-orbital systems are challenging targets to investigate except few cases where a good method for a certain circumstance exists. The main factors that affect the difficulty are size and symmetry of the impurity Hamiltonian. The total number of orbitals N_s is the sum of the number of correlated orbitals N_c and the number of noninteracting bath orbitals N_b. The most popular solver for the DMFT at this moment is arguably continuous-time QMC (CTQMC) [9], and the second would be the ED [10]. The QMC can barely access $N_c \sim 5$ under low symmetry situation and the ED can solve $N_s \sim 14$ no matter whether the orbitals are interacting or not. This is insufficient in most cases since even the impurity part needs more orbitals to capture local quantum fluctuations.

Fortunately, even few more orbitals in the impurity Hamiltonian enhance the capability to describe the physics significantly [11]. It can be achieved by exploiting the sparsity structure of the impurity Hamiltonian. Since the bath orbitals are completely noninteracting, not every Slater determinant is equally important in the Hilbert space: a substantial portion of exponentially growing Hilbert space is overinvestment. On the other hand, systematic methods to exclude the redundant Slater determinants have been widely used in quantum chemistry [12]. The systematically truncated Hilbert spaces enable us to access larger impurity Hamiltonians capturing essential physics of the system than cannot be solved in the original ED [13, 14].

There are two directions to increase the number of orbitals in the impurity Hamiltonian: increasing the number of correlated orbitals N_c or the number of bath orbitals N_b. First I implemented the generalized active space formalism in quantum chemistry [15] to relax restriction on N_b. By fully exploiting the noninteracting nature of bath orbitals, we could include much more bath orbitals than previous works [11, 14]. In the previous work, the improved spectral description by more bath orbitals explained the strong gap edge optical conductivity in high-T_c cuprates, and more impurity orbitals were expected to smooth the over-concentrated conductivity at gap edge [11].

Increasing N_c requires more controlled methods. To relax the restriction on N_c, I have developed a new impurity solver based on the truncated Hilbert space where the Slater determinants are adaptively selected in iterative way [16]. The solver can solve the impurity Hamiltonian with eight correlated orbitals and sufficient number of bath orbitals to describe environments, and it provides reliable spectrum on the real-frequency axis without any complicated post-processes. In the benchmark study on the one-dimensional Hubbard model,

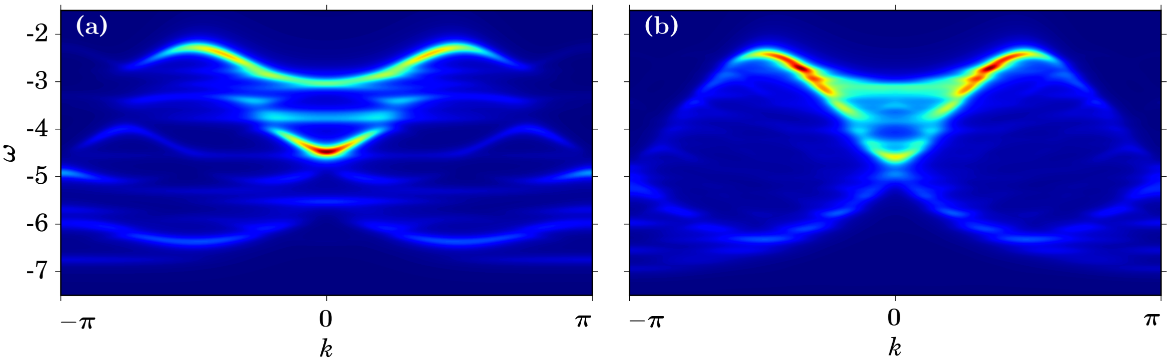

Figure 1: Spectral weights of the one-dimensional Hubbard model for $U/t = 8$ computed (a) by DMFT+ED with $(N_c, N_b) = (4, 8)$ and (b) by DMFT+new impurity solver with $(N_c, N_b) = (8, 16)$. Doubled number of orbitals in the impurity Hamiltonian improves description on the spin-charge separation significantly.

which is well-known but not trivial, it shows superior description of spectrum reproducing known properties such as spin-charge separation in Fig. 1. This capability would be even more useful in general multi-orbital problems. Although it was initially motivated by the need on better DMFT calculations, the application is not limited in the context of the DMFT. Further optimization and development of the impurity solver will enable us to study potentially interesting target systems which could not be handled by existing methods, with or without the DMFT.

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2.10 Weyl rings and enhanced susceptibilities in pyrochlore iridates: k·p analysis of cluster dynamical mean-field theory results

R. Wang, A. Go, A. Millis

Pyrochlore iridates, $R_2\text{Ir}_2\text{O}_7$, is oxide compounds where R is rare earth or yttrium. Valence electron of iridium and oxygen ions governs transport of this materials while the rare earth ions are electronically inert. Since the electrons from iridium ions are in $5d$ orbitals, both spin-orbit coupling and mutual Coulomb interaction are comparable to the band width. We focussed R=Eu and Y case, where we can neglect the magnetic moment of the rare earth ions. Depending on the result of their competition, the system reveals drastically different characteristics. Theoretical models targeting pyrochlore iridates have shown very rich phase diagram, including topological transitions, axion insulators, Weyl semimetals [1–6].

Many experimentalists are working on the pyrochlore iridiates to realize the interesting theoretical proposals. Because of subtle competition between comparable energy scales, tiny tuning of external parameters may lead unexpected phase transitions. Electronic structure calculation via density functional theory (DFT) in combination with the dynamical mean-field theory (DMFT) [7, 8] can provide valuable information to identify promising parameter range to search. Previous DFT+DMFT calculations on this material reported no Weyl semimetallic phase [10, 11]. The important assumption in earlier work is that the self-energy is site-local and all t_{2g} orbitals are active. We conducted the DFT+DMFT computation where the exact diagonalization [9] is employed as an impurity solver. We found that the non-local quantum correlation is critical to observe Weyl points [12]. Further detailed computation shows that one can stabilize the Weyl semimetal in a very narrow range of interaction strength [13]. Only cluster DMFT gives the intermediate Weyl phase between metal and insulator, while the single-site DMFT suggest a direct metal-insulator transition.

This result is technically important, showing that choice of *unit* in the DMFT calculation may yield different solutions, especially near the phase transitions. It is closely related to the number of electrons in the unit cell. The Ir ion has d^5 electronic configurations in $R_2\text{Ir}_2\text{O}_7$. If one considers a single Ir ion, the number electrons for the site would be five, which is an odd number. However, once we include all four Ir ions in a unit cell of the pyrochlore lattice, the total number of electrons becomes an even number, twenty. The effect of even-odd alternation in a unit cell has been known in the one-dimensional Hubbard model [14], but to our best knowledge, no result has been reported in three-dimensional multi-orbital case. This indicates that one needs to put extra care on setting the number of electrons in the DMFT calculations, when the focuss of the calculation is phenomena near the metal-insulator transition.

More remarkably, we verified interesting properties in the observed Weyl phase. First, the location of the Weyl points are very close to the Brillouin zone plane, preserving C_3 rotational symmetry of the lattice. Due to the short distance between the plane and the Weyl points, the spectral weights appears ring-shape as illustrated in Fig. 1. Unlike the conventional Weyl semimetal where the Weyl points exist on the Fermi level, the Fermi surface can be approximated to be the Weyl ring in this system. To analyze the physical consequences of the spectrum, we used $k \cdot p$ theory and constructed effective Hamiltonian describing energy dispersions near the Fermi level. Based on the solution, we computed the optical conductivity and magnetic susceptibility. We estimated the signature of the Weyl phase in terms of the optical response would be order of THz.

The control parameter of the phase transition is the Coulomb interaction strength, which

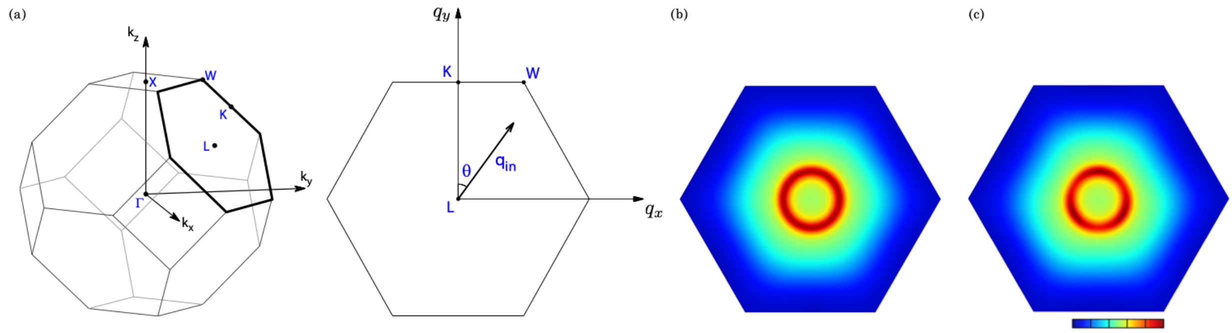

Figure 1: (a) Brillouin zone of the face-centered cubic lattice and (b-c) spectral weights in the Weyl semimetallic phase on a plane perpendicular to Γ-L line, which defines the in-plane vector q_{in} and out-of-plane direction q_z. In (a), a hexagonal zone boundary out of eight planes is plotted separately. The plane corresponds to $q_z = 0$ in (b). The Weyl points are located slightly away of the plane as shown in (c) with $q_z \sim 0.001\pi$.

can be tuned by applying pressure in experiments. In reality, all the experiments are performed in non-zero temperature and we expect that the same transition would be observed by raising temperature. The detailed temperature dependence is valuable information to guide experiments to find the Weyl phase in pyrochlore iridates. Unfortunately, the transition temperatures is exceedingly high to resolve response functions based on our calculation, because the exact diagonalization solver can attack zero or very low temperature. According the experimental metal-insulator phase diagram, replacing R to Nd decreases the transition temperature down to 22K, which is ideal to us. To consider the temporal fluctuations, we initiated the DFT+DMFT project for $Nd_2Ir_2O_7$, including the f-d exchange interaction in a mean-field level. Observing the evolution of the phase transitions under the magnetic field would be fascinating future works.

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2.11 Reconfigurable topological phases in next-nearest-neighbor coupled resonator lattices

D. Leykam, S. Mittal, M. Hafezi, Y.D. Chong

Topological photonic systems are of interest not only because they reveal interesting and exotic physical effects, but also for their promising potential applications such as disorder-robust waveguides and delay lines [1]. However, an outstanding challenge is to design reconfigurable or switchable topological photonic waveguides that are able to route signals between different destinations on demand. So far this idea was only demonstrated in the microwave frequency range and required mechanical switching that is not scalable to higher frequencies [2].

Here we report a novel design supporting this desirable reconfigurability in the technologically-important optical frequency range, where switching can be induced using electro-optic or thermal modulation or optical nonlinearities [3]. Our approach is based on exploiting a novel degree of freedom for the design of topological optical resonator lattices: next-nearest neighbour coupling. With this, we can obtain topological edge states in comparatively simple lattices without requiring additional modulation of the resonators in time or space. Moreover, transitions between trivial and nontrivial phases can be induced by resonance frequency shifts that are small compared to the resonators' free spectral range. These features are thus promising not only for potential applications in reconfigurable optical devices, but also of fundamental interest for exploring how optical nonlinearities may affect topological edge states.

Our model is schematically illustrated in Fig. 1(a). We consider a two-dimensional bipartite square lattice, formed of resonant "site rings" that are coupled by off-resonant "link rings" whose resonances are detuned by $\Delta\nu$. The latter are positioned to mediate both nearest- and next-nearest neighbour coupling between the sites. As in previous studies of ring resonators [4], we focus on a single circulation of light (clockwise) within the site rings, which effectively breaks the time reversal symmetry and in combination with the next nearest neighbour coupling enables the formation of topological edge states. In the limit of the coupling being weak compared to the rings' free spectral range FSR, light propagation in the lattice is governed by the following tight binding Hamiltonian:

$$\hat{H} = \sum_{x,y} \left(\hat{H}_a + \hat{H}_b + \hat{H}_{ab} + \hat{H}_{ab}^\dagger \right), \tag{1}$$

$$\hat{H}_a = \hat{a}_{x,y}^\dagger \left(\nu_a \hat{a}_{x,y} + J \csc\frac{\phi}{2} \sum_{\pm} \hat{a}_{x,y\pm1} \right),$$

$$\hat{H}_b = \hat{b}_{x,y}^\dagger \left(\nu_b \hat{b}_{x,y} + J \csc\frac{\phi}{2} \sum_{\pm} \hat{b}_{x\pm1,y} \right),$$

$$\begin{aligned}\hat{H}_{ab} = J e^{i\phi/4} \csc\frac{\phi}{2} [&\hat{a}_{x,y}^\dagger (\hat{b}_{x,y} + \hat{b}_{x+1,y+1}) \\ &+ \hat{b}_{x,y}^\dagger (\hat{a}_{x-1,y} + \hat{a}_{x,y-1})],\end{aligned}$$

$$\nu_a = 2J\cot\frac{\phi}{2} + M, \quad \nu_b = 2J\cot\frac{\phi}{2} - M,$$

where $\hat{a}^\dagger, \hat{b}^\dagger$ create photons on the a, b sublattices respectively, integers (x, y) index the lattice sites, J is the inter-resonator coupling, M is a detuning between the two sublattices, and $\phi = 2\pi\Delta\nu/\mathrm{FSR}$ parametrizes the hopping phase accumulated in the link rings. Note in particular that the nearest and next-nearest neighbour coupling strengths are equal in magnitude, a feature not easy to achieve in photonic lattices based on coupled waveguides.

We obtain the single particle energy eigenvalues $\delta\nu$ of $\hat{H}$ by Fourier transforming to obtain its corresponding Bloch Hamiltonian. This also allows computation of the topological invariant characterizing its bands, the Chern number. Fig. 1(b) shows the results of the analytical band structure calculation. We see that for small sublattice detunings M, the two bands associated with the resonant sites are in a topological Chern insulator phase, characterised by unidirectional edge states protected by disorder. Note that we effectively break the time reversal symmetry by assuming excitation of a clockwise mode of the site rings; if instead an anticlockwise mode is excited, edge states with opposite velocity will be obtained, as required by the time reversal symmetry of the full system. At $M = 2J\csc\frac{\phi}{2}$ the system undergoes a transition to a trivial insulator phase without topological edge states. Interestingly, when the coupling strength J is small, this transition can be induced by similarly small tuning of M, accessible via electro-optic or thermo-optic effects.

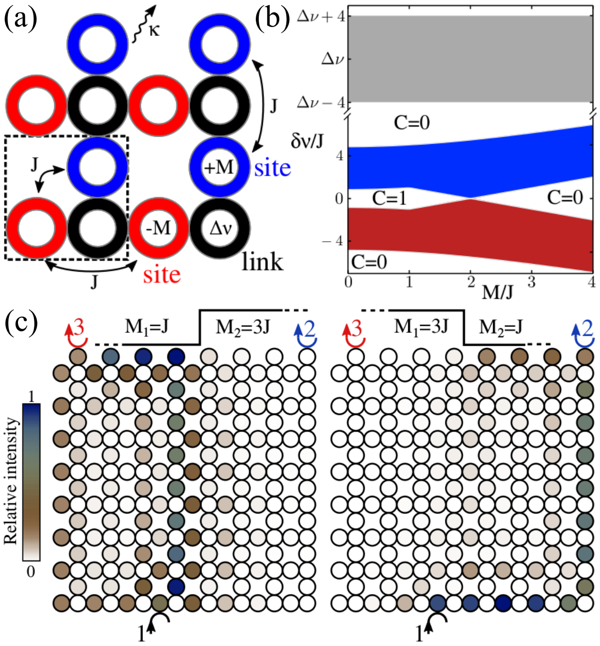

Figure 1: (a) Square resonator lattice consisting of site rings (blue, red) with relative detuning M, intrinsic loss κ, and coupling of strength J mediated via off-resonant link rings (black). (b) Lattice energy spectrum $\delta\nu$ (shaded regions) as a function of the detuning M. The shading indicates the sublattice the modes are most strongly localized to for large M. Gap Chern numbers C are indicated. (c) Selective routing of a mid-gap ($\delta\nu = 0$) topological edge state from an input port (1) to output ports (2) or (3) via reconfiguration of an interface between domains with different detunings $M_{1,2}$.

Fig. 1(c) shows how we can modulate the detuning M to actively control the propagation of topological edge states through a lattice. We consider a lattice consisting of two domains with different detunings M_1, M_2 in the left and right halves, respectively, with all other lattice parameters kept identical. By suitably choosing these detunings, we can design the lattice to host a domain wall between trivial and non-trivial phases; such a domain wall will support a topological edge state. Depending on the orientation of the domain wall, a signal initially input at the lower side of the lattice (at port 1) will follow either the edge of the lattice or the domain wall, exiting the lattice at output ports 2 or 3 respectively. This transmission is robust to moderate disorder in the lattice, limited only by the losses κ within the individual rings, thus demonstrating a reconfigurable topologically-protected waveguide design scalable to optical frequencies.

Finally, we briefly comment on potential device applications. Thermo-optic modulators are capable of tuning M by hundreds of GHz [4], thus our design enables the implementation of reconfigurable topologically protected transmission bands of width of up to 200–300 GHz, which would be promising for wavelength division multiplexing applications. Alternatively, weaker electro-optic or nonlinearly-induced resonance shifts of up to 50 GHz are feasible with current silicon photonics technology and could be used to implement similar switching over a smaller bandwidth. Thus, our novel design provides a promising platform for achieving reconfigurable topological waveguiding at optical frequencies.

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2.12 Observation of valley Landau-Zener-Bloch oscillations and pseudospin imbalance in photonic graphene

Y. Sun, D. Leykam, S. Nenni, D. Song, H. Chen, Y.D. Chong, Z. Chen

When a particle in a lattice experiences a weak uniform force it undergoes a periodic motion known as Bloch oscillations (BO), due to the periodicity of the energy band structure. A net acceleration and transport of the particle requires stronger forces, which destroy the adiabatic BO by inducing interband Landau-Zener tunneling (LZT). Originally observed in semiconductor superlattices [1], more recently BO and LZT have been employed to measure geometrical and topological properties of gapped energy bands via spatial shifts of wavepackets [2].

Non-adiabatic phenomena related to BO and LZT in gapless systems remain poorly understood and most extensively studied only in one-dimensional lattices. Two-dimensional systems exhibit more complex behaviour, with e.g. the BO and LZT sensitive to the direction of the applied field [3]. A particularly interesting question is the behaviour of BO and LZT at Dirac points occurring in two-dimensional materials such as graphene [4], where the energy gap vanishes and the LZT probability is predicted to become sensitive to the Dirac point's chirality [5]. However, to our knowledge, BO through directly through Dirac points and the role played by the Dirac point chirality have never been demonstrated in experiment.

Here, we report the observation of BO and LZT at the Dirac points in a "photonic graphene" optically-induced waveguide lattice [6]. We find non-adiabatic wavepacket dynamics sensitive to the direction of an applied force. When the force preserves graphene's sublattice symmetry, persistent and symmetric BO that visit both Dirac points occur, due to perfect LZT through each Dirac point. On the other hand, when the force breaks the sublattice symmetry, we observe damped BO confined to a single Dirac point and imperfect LZT. Counterintuitively, in this case the LZT probability decreases as the strength of the driving force is increased. We introduce a simple theoretical model explaining this behaviour in terms of the wave effective mass becoming proportional to the force.

Fig. 1(a) shows our experimental setup, based on a honeycomb lattice optically induced in a biased photorefractive crystal. An additional transverse refractive index gradient (analogous to an applied force) is induced by laterally illuminating the crystal with white light partially blocked by a razor blade. The propagation of a probe beam through the crystal is described by the paraxial equation for the normalized electric field envelope $\psi(x,y,z)$,

$$i\partial_z\psi = -\frac{\lambda}{4\pi n_0}\nabla_\perp^2\psi - \frac{2\pi}{\lambda}\Delta n(x,y)\psi, \qquad (1)$$

where z is the propagation distance, $\lambda = 488$ nm is the wavelength in vacuum, $n_0 = 2.36$ is the ambient refractive index of the crystal, $\nabla_\perp^2 = \partial_x^2 + \partial_y^2$ is the transverse Laplacian, and Δn accounts for the honeycomb lattice [shown in Figs. 1(b,c)] and index gradient.

In the experiment we cannot directly monitor the beam evolution throughout the crystal, but we can emulate its behaviour by observing the output profile in momentum space for various input tilts (initial momenta) of the probe beam. Representative output spectra for a horizontal index gradient are shown in Fig. 1(d) and give a complete picture of the beam evolution during one BO through the two inequivalent Dirac points. In particular, after one cycle the input state is restored, due to the perfect (and symmetric) LZT at each Dirac point.

In contrast, a vertical index gradient induces BO between equivalent K points of the lattice, i.e. confined to a single Dirac point. Typical results are illustrated in Fig. 1(e), revealing highly asymmetric scattering at the Dirac point, leaving the beam split between the first and second bands after one BO cycle. Thus, the LZT is strong but imperfect.

To explain these different behaviours, we construct an analytically solvable Landau-

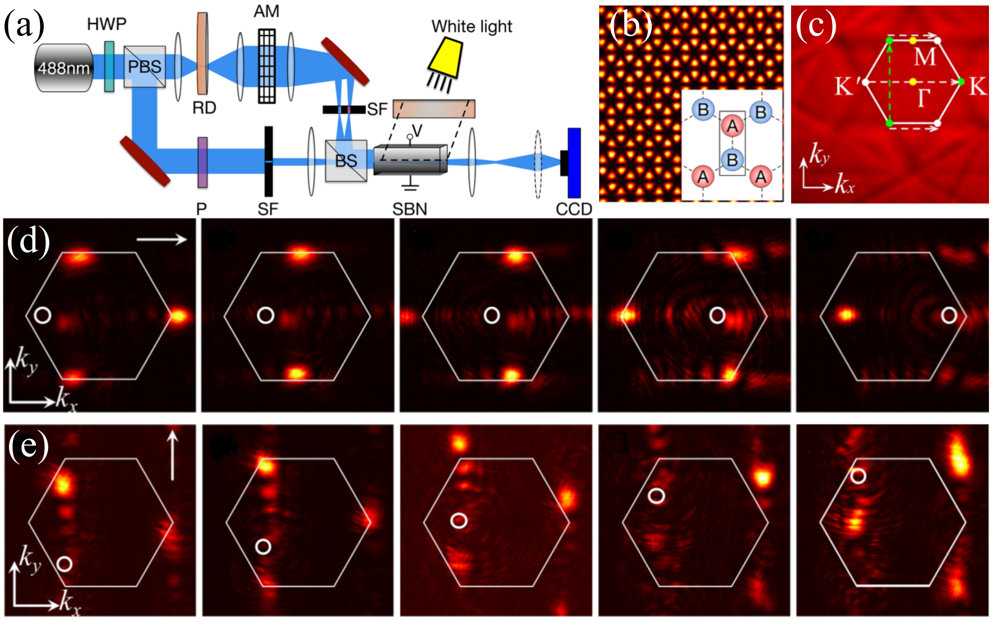

Figure 1: (a) Schematic of the experimental setup. The upper path is for optical induction of photonic graphene, and the bottom path is for probing through the lattice. (b) Honeycomb lattice intensity pattern, with inset showing two sublattices. (c) Measured Brillouin zone spectrum, illustrating inequivalent Dirac points K, K' and BO trajectories. (d,e) Measured Fourier spectra for BO under horizontal (d) and vertical (e) index gradients. White circles indicate input tilt.

Zener Hamiltonian describing the tunnelling in the vicinity of the Dirac points that is valid for sufficiently weak index gradients, when LZT away from the Dirac points can be safely neglected [6]. We obtain the LZT probability

$$P_{LZT} = \exp\left(-\frac{2\pi(\boldsymbol{E}\cdot\boldsymbol{\delta}/2)^2}{\sqrt{3}|\boldsymbol{E}|Ca}\right), \qquad (2)$$

sensitive to the direction of the applied gradient $\boldsymbol{E}$ relative to the displacement between the two inequivalent sublattices, $\boldsymbol{\delta}$ (other parameters are the lattice period a and inter-site coupling strength C). This reproduces the observed perfect tunnelling for the horizontal gradient ($\boldsymbol{E}\cdot\boldsymbol{\delta} = 0$), and imperfect tunnelling for the vertical gradient ($\boldsymbol{E}\cdot\boldsymbol{\delta} = Ea/2\sqrt{3}$). The interplay between the index gradient and sublattice symmetry breaking at the Dirac points thus leads to novel BO and LZT dynamics.

In summary, our observations of asymmetric scattering and LZT reveal that Dirac points, which have an isotropic energy spectrum, can respond anisotropically to driving fields. This anisotropy originates from the nontrivial chirality of the Bloch wave eigenfunctions in the vicinity of the Dirac points. This effect may be used to help control valley and sublattice degrees of freedom in graphene-like systems, and may also provide insights into related BO phenomena in parity-time symmetric, flat band, and spin-orbit coupled lattice systems.

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2.13 Reconfiguration of quantum states in $\mathcal{PT}$-symmetric quasi-one dimensional lattices

J.-W. Ryu, N. Myoung, H.C. Park

We demonstrate mesoscopic transport through quantum states in quasi-1D lattices maintaining the combination of parity and time-reversal ($\mathcal{PT}$) symmetries by controlling energy gain and loss [1]. We investigate the phase diagram of the non-Hermitian system where transitions take place between unbroken and broken $\mathcal{PT}$-symmetric phases via exceptional points (EPs). Quantum transport in the lattice is measured only in the unbroken phases in the energy band–but not in the broken phases. The broken phase allows for spontaneous symmetry-broken states where the cross-stitch (CS) lattice is separated into two identical single lattices corresponding to conditionally degenerate eigenstates. These degeneracies show a lift-up in the complex energy plane, caused by the non-Hermiticity with $\mathcal{PT}$-symmetry.

First, we consider a CS lattice, as shown in the inset of Fig. 1, the non-Hermitian Hamiltonian can be expressed on the up/down basis of Pauli matrix $\boldsymbol{\sigma} = (\sigma_x, \sigma_z)$ and identity matrix σ_0, and in terms of vector field $\boldsymbol{h}(k) = (-t - 2d\cos k, \delta/2 + i\gamma/2)$ and extra term $h_0 = -2d\cos k$, as

$$H(k) = \boldsymbol{h}(k) \cdot \boldsymbol{\sigma} + h_0(k)\sigma_0, \tag{1}$$

where, using Bloch theorem, t and d are hopping constants of intra and inter unit cells, and δ and γ are real asymmetric energy and balanced gain and loss on site, respectively. The eigenvalues of the Hamiltonian are

$$\varepsilon_\pm = -2d\cos k \pm \sqrt{(t + 2d\cos k)^2 + \left(\frac{\delta + i\gamma}{2}\right)^2},$$

which are complex, as $\varepsilon = \varepsilon_r + i\varepsilon_i$. Figure 1 (b)-(e) show complex energy bands for the CS lattice.

Next, let us consider charge transport in a $\mathcal{PT}$-symmetric quasi-1D lattice, specifically here in a CS lattice with N unit cells between two leads connected to both lattice ends. The Hamiltonian for this model is given by

$$H = H_{cs} + H_{lead} + H_{coupling}, \tag{2}$$

where H_{cs}, H_{lead}, and $H_{coupling}$ describe the CS lattice, leads, and coupling between the lattice and leads, respectively. Each Hamiltonian is written as follows:

$$\begin{aligned} H_{cs} &= \sum_{i=1}^{N} H_0 c_i^\dagger c_i + \sum_{i=1}^{N-1} (H_1 c_{i+1}^\dagger c_i + h.c.) \\ H_{lead} &= -\frac{V_0}{2} \sum_{j\neq 0} (b_{j+1}^\dagger b_j + h.c.) \\ H_{coupling} &= -g(c_1^\dagger b_{-1} + b_1^\dagger c_N + h.c.), \end{aligned}$$

where $H_0 = -t\sigma_x + (\delta/2 + i\gamma/2)\sigma_z$, $H_1 = -d(\sigma_x + \sigma_0)$, and $c_j^\dagger$ (c_j) and $b_j^\dagger$ (b_j) are creation (annihilation) operators for the lattice and leads, respectively. $V_0/2$ is hopping strength in the leads and g is coupling strength between the ends of the CS lattice and leads. If the wavenumber in the leads is q, then the wavefunction in the leads is given by $\phi_j = e^{iqj} + r_0 e^{-iqj}$ ($j < 0$) and $\phi_j = t_0 e^{iqj}$ ($j > 0$), where $|r_0|^2$ and $|t_0|^2$ are reflection and transmission probabilities, respectively, with $|r_0|^2 + |t_0|^2 = 1$ in $\mathcal{PT}$-symmetric cases. Using $e^{\pm iq} = -E/V_0 \pm i\sqrt{1 - |E/V_0|^2}$, we obtain transmission probabilities from the resulting $(2N+2) \times (2N+2)$ matrix, where E is the incident energy from a lead.

In Fig. 1 (f), the transmission probability $T = |t_0|^2$ is oscillating as a function of energy E, and balanced gain and loss γ and the oscillation peaks are indicated resonances with eigenenergies as shown in (g)–(j). There exists transmission suppression, which makes the boundaries the same as the band edges for the unbroken phase in Fig. 1 (a).

Compared to typical transport characteristics in Hermitian systems, an intriguing transport phenomenon has been revealed in a non-

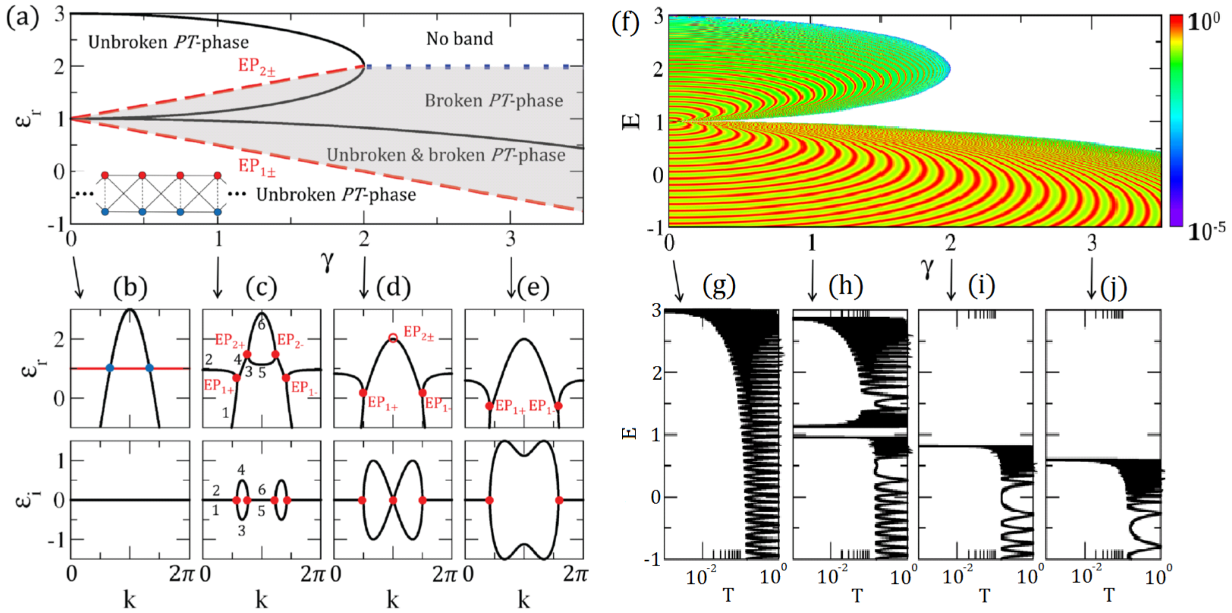

Figure 1: (a) Phase diagram of $\mathcal{PT}$-symmetric CS lattice. Black curves represent the band edges of unbroken $\mathcal{PT}$-symmetric phase ε^*. There are two red dashed lines of EPs inside the unbroken $\mathcal{PT}$-symmetric phase regions: $EP_{1\pm}$ and $EP_{2\pm}$. The shaded region indicates the broken $\mathcal{PT}$-symmetric phase, which includes a coexistent region with unbroken and broken phases. The blue dotted line is the critical energy $\varepsilon_c = 2d$. (Inset) $\mathcal{PT}$-symmetric CS lattice with coupling strengths t (dashed lines) and d (solid lines). (b) Complex energy band for the CS lattice. (c)-(e) Complex energy bands with different non-Hermitian imbalanced potentials. The red dots are EPs. (f) Transmission probabilities in the CS lattice with $N = 100$ unit cells in (γ, E) space. Red curves represent high transmission probabilities corresponding to the resonant modes in the finite $\mathcal{PT}$-symmetric CS lattice. (g)-(j) Transmission probabilities with different γ. As E approaches the band edges, the spacings between transmission peaks narrow because of the high density of states.

Hermitian system: the suppression of transmission in an energy range that corresponds to the broken phases between the band edges of the unbroken phases. Such suppression phenomena can be intuitively understood by the concept of group velocity. Because of the imaginary imbalanced potential, the eigenenergies of the non-Hermitian system are given as complex numbers, and accordingly, the group velocity, i.e. $d\varepsilon/dk$, is expected to be complex. While real group velocity corresponds to propagating modes, imaginary group velocity is reflected in evanescent modes. Interestingly, in the broken phase, the group velocity has been found to be a complex number, of which the imaginary part is reflected in the suppression of the transmission due to the attenuation of the evanescent modes.

In summary, a reconfiguration of quantum states in $\mathcal{PT}$-symmetric quasi-1D lattices has been demonstrated, where the quantum states can be controlled by balanced gain and loss. We have explored how the variations of quantum states originate in the transition from the unbroken to broken $\mathcal{PT}$-symmetric phase, via EP. As a result, transmission probabilities in the $\mathcal{PT}$-symmetric system are only determined by bands with an unbroken phase. Conversely, in the case of a non-$\mathcal{PT}$-symmetric system with overall gain and loss, transmission probability is determined by the broken $\mathcal{PT}$-symmetric phase of corresponding $\mathcal{PT}$-symmetric systems with a shift in imaginary energy by the amount of overall gain and loss.

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2.14 Magnetically induced transparency of a quantum metamaterial composed of twin flux qubits

K.V. Shulga, E. Il'ichev, M.V. Fistul, I.S. Besedin, S. Butz, O.V. Astafiev, U. Huebner, A.V. Ustinov

Superconducting quantum metamaterials (SQMs) are novel artificially prepared solid state structures whose electrodynamic properties are expected to govern by peculiar interplay of classical Maxwell electrodynamics and quantum-mechanical laws [1,2]. The SQMs are composed of a large amount of quantum objects acting as artificial atoms. These macroscopic quantum objects, i.e. superconducting *qubits* that usually modelled as two-level system, can be arranged in different one- or two-dimensional lattices forming various networks of strongly interacting qubits.

Embedding of such networks in a low-dissipative transmission line allows one to study the electromagnetic waves (EWs) propagation through the SQMs and to obtain novel light-matter interaction phenomena. Propagation of EWs through such a medium is accompanied by excitations of intrinsic quantum transitions within individual meta-atoms and modes corresponding to the interactions between them. A complete experimental control of the transition frequencies of individual qubits are achieved by application of small magnetic fields, and therefore, one can expect a large variation of EWs transparency in the SQMs. However, the only reported to date experiments with the SQMs in the quantum regime employed arrays of superconducting qubits *weakly* coupled to a microwave resonator [3, 4]. The observed variations of the transmission coefficient were, in that case, rather small and limited to a narrow frequency range.

In our work published in the *Nature Communication (2018)* [5], we were aimed at achieving strongly tunable electromagnetic properties of the SQMs in a wide frequency range, not limited by the qubit–resonator interaction. To realize that we have used the specific SQMs fabricated from an array of meta-atoms, each consisting of a pair of superconducting loops coupled via a tunnel junction (*twin flux qubit*), see the Fig. 1.

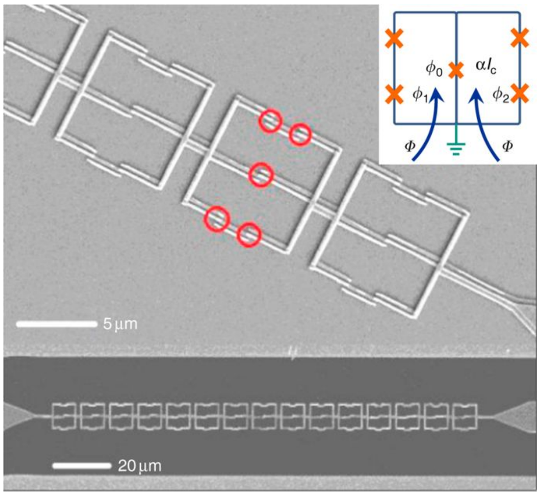

Figure 1: A quantum metamaterial made of twin flux qubits. Each qubit consists of two superconducting loops sharing one common central Josephson junction (α-junction) and four identical Josephson junctions located on the outer parts of the loops.

Such meta-atoms provide a strong coupling between qubits and propagating electromagnetic waves. Moreover, twin-qubits structures support penetration of single magnetic fluxes in each twin-qubit and corresponding $0 \rightarrow \pi$ transition of the central Josephson α -junction phases leading to an abrupt suppression of the microwave transmission in a broad frequency range, see the Fig. 2a,c. In particular, the transmission displays the sharp changes under variation of the magnetic flux Φ. In the Fig. 2 one can see two different ranges of microwave propagation, nearly flat transmission around zero field and sharp resonant enhancement of the transmission near 11–14GHz at magnetic flux $\Phi \simeq \Phi_0/2$. Such resonant transparency also controlled by an external magnetic field, is the fingerprint of qubits $|0 > \rightarrow |1 >$ transitions. We anticipate various applications of the observed frequency-tunable transparency in the

SQMs.

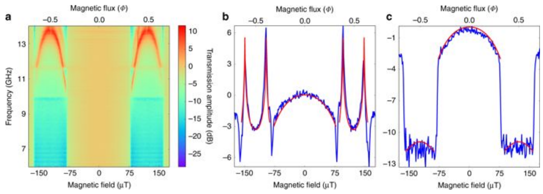

Figure 2: Transmission of microwaves through the SQM in different regimes. **a)** The color plot of measured dependence of the amplitude of transmission coefficient on applied dc magnetic field and frequency f. **b)** A cross-cut of a color plot at the fixed frequency of $13GHz$. The sharp peaks correspond to the resonant transmission of EWs **c)** A cross-cut of a color plot at the fixed frequency of $10GHz$. The sharp jumps correspond to a transition between zero and π phase on the central junction of the twin qubit. Red curve is a fit to the theoretically predicted dependence.

In order to quantitatively analyze these experimental features, we have developed and analyzed a model of EWs propagation through the low-dissipative transmission line which is strongly inductively coupled to a periodic array of quantum oscillators. The transmission line is characterized by coordinate and time dependent charge distribution $Q(x,t)$. Here, x is the coordinate along the transmission line. In the presence of a periodic array of twin qubits, which can be considered as SQUID-like quantum oscillators, we have derived the effective equation for EWs of frequency ω propagating through the SQMs:

$$Q_{n+1} + Q_{n-1} -$$

$$-2\left[Q_n cos(ka) - \frac{\beta\{Q_n\}}{2kc_0^2} sin(ka)\right] = 0 \qquad (1)$$

where $Q_n = Q(x_n)$, x_n is the position of nth qubit in the array, $\omega = c_0 k$ and βQ_n is expressed in the linear regime as

$$\beta \simeq -K(\omega)Q, K_(\omega) = \frac{\omega_p^2}{\Omega^2 - \omega^2 + i\gamma_J}\ , \qquad (2)$$

where ω_p and Ω are the plasma frequency of Josephson junctions and the qubit frequency, accordingly. In the limit of dense qubit arrays we obtain the dependence of the transmission coefficient S_{21} on the magnetic field and the frequency of EWs as (ℓ is the length of the array)

$$|S_{21}|^{-1} =$$

$$= \left|\cos(k\ell\sqrt{AK(\omega)}) + i\frac{\sqrt{AK(\omega)}}{2}\sin(kl\sqrt{AK(\omega)}\right|, \qquad (3)$$

where A is the coupling strength of qubits array with the transmission line. This equation quantitatively explains all experimental features. Indeed, Eq. 3 shows a strong dependence of the transmission coefficient on the characteristic frequency ω. In particular, there is a non-resonant suppression of S_{21} due to a great enhancement of $K(\omega)$ in the 0-state. However, as resonant condition is satisfied, i.e., $k\ell\sqrt{AK(\omega)} = \pi$, the qubit array becomes transparent. Our detailed quantitative analysis is in a good accord with measurements (see the fitting in Fig. 2).

This work is the result of a scientific collaboration between various Universities of Russia, Germany and Republic of Korea.

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2.15 Spontaneous polariton currents in periodic lateral chains

A.V. Nalitov, T.C.H. Liew, A.V. Kavokin, B.L. Altshuler, Y.G. Rubo

Recently, there is growing interest of polariton community in the properties of chains and lattices made of polariton condensates, motivated by possible applications for classical [1,2] and quantum [3] computation. In this work [4] we have studied closely related problem of out-of-equilibrium polariton condensation in one-dimensional periodic structure. We predict spontaneous generation of superfluid polariton currents in planar microcavities with lateral periodic modulation of both potential and decay rate. A spontaneous breaking of spatial inversion symmetry of a polariton condensate emerges at a critical pumping, and the current direction is stochastically chosen. We analyze the stability of the current with respect to the fluctuations of the condensate. A peculiar spatial current domain structure emerges, where the current direction is switched at the domain walls, and the characteristic domain size and lifetime scale with the pumping power.

We solve the Gross-Pitaevskii equation (GPE) for the condensate wavefunction Ψ taking into account two types of nonlinearities, stemming from polariton repulsion and reservoir depletion ($\hbar = 1$):

$$\mathrm{i}\frac{\partial\Psi}{\partial t} = \left[-\frac{1}{2m}\frac{\partial^2}{\partial x^2} + U(x) + \frac{\mathrm{i}}{2}\left(W - \frac{\eta}{2}\langle|\Psi|^2\rangle\right) + \alpha|\Psi|^2\right]\Psi. \quad (1)$$

Here m is the polariton effective mass and α is the interaction constant. The pumping power W, determined by reservoir population, is locally reduced due to its depletion, which is proportional to the average condensate density with the prefactor $\eta/2$.

We assume that the periodic potential U [$U(x) = U(-x)$ and $U(x) = U(x + a)$] yields the single-polariton band structure with the longest (shortest) lifetime characterizing the lowest-band top (the second-band bottom) state, which we denote as S(A). In the nearly free particle approximation, the two polariton modes $\Psi_S \propto \cos(k_0 x)$ and $\Psi_A \propto \sin(k_0 x)$ with $k_0 = \pi/a$ are separated by the energy band gap ε and decay at rates $\Gamma - \gamma$ and $\Gamma + \gamma$, respectively.

One expects the longest lifetime mode (S) to cross the lasing threshold first with increasing pumping power. With further growth of the condensate population the repulsive interaction blueshifts the condensate and eventually leads to admixture of the second band bottom (A) state. Therefore, we project Eq. (1) onto the plane-wave two-mode basis and search for the solution in the form $\Psi = \psi_+ \exp(+\mathrm{i}k_0 x) + \psi_- \exp(-\mathrm{i}k_0 x)$. Assuming that the envelopes $\psi_\pm$ are smooth on the scale of the lattice constant a we neglect second spatial derivatives of $\psi_\pm$ and obtain

$$\left[\frac{\partial}{\partial t} \pm c\frac{\partial}{\partial x} + \frac{g(s)}{2} + \frac{\mathrm{i}\alpha}{2}(3s \mp s_z)\right]\psi_\pm = \frac{\gamma + \mathrm{i}\varepsilon}{2}\psi_\mp. \quad (2)$$

Here $c = \pi/ma$, $g(s) = \eta s - w$ with $w = W - \Gamma$, $s = (|\psi_+|^2 + |\psi_-|^2)/2$, and $s_z = (|\psi_+|^2 - |\psi_-|^2)/2$.

First we consider x-independent solutions of (2), given by $\psi_\pm(t) = \sqrt{s \pm s_z}\, e^{-\mathrm{i}(\Omega t \pm \phi)}$ with time-independent s, s_z, the phase shift ϕ, and the emission frequency Ω (counted from the middle of the gap). We show that the S condensate (with $\psi_+ = \psi_-$) becomes unstable at some critical pumping. Depending on the parameters, there are two regimes corresponding to subcritical and supercritical pitchfork bifurcation. We refer to them as to transitions of types I and II, respectively, in analogy to phase transitions of the first and the second order. We note that the solutions formed after pitchfork bifurcation possess different occupations of left- and right-movers, $|\psi_+| \neq |\psi_-|$, and there appears a spontaneous current flowing in the structure with the density $j = 2k_0 s_z/m$. The formation of this spontaneous current is the main result of the work.

Then we study the stability with respect to inhomogeneous phase and population fluctuations, by calculating the elementary excitation spectra. In the standard way, we linearize Eq. (2) with respect to plane wave perturbation

$$\delta\psi_{\pm} = e^{-\mathrm{i}\Omega t}\left(u_{\pm}e^{\mathrm{i}kx+\lambda t} + v_{\pm}^{*}e^{-\mathrm{i}kx+\lambda^{*}t}\right) \quad (3)$$

of the spatially uniform solutions described above. The dispersion of the real and imaginary parts of the Lyapunov exponent $\lambda(k)$ for the nonzero current solution is plotted in Fig. 1 for different regimes. Uniformly stable solutions are characterized by three modes with $\mathrm{Re}\lambda(0) < 0$ and one Goldstone mode with $\lambda(0) = 0$. The Goldstone mode appears due to the irrelevance to the global shift of the total phase of the condensate Φ.

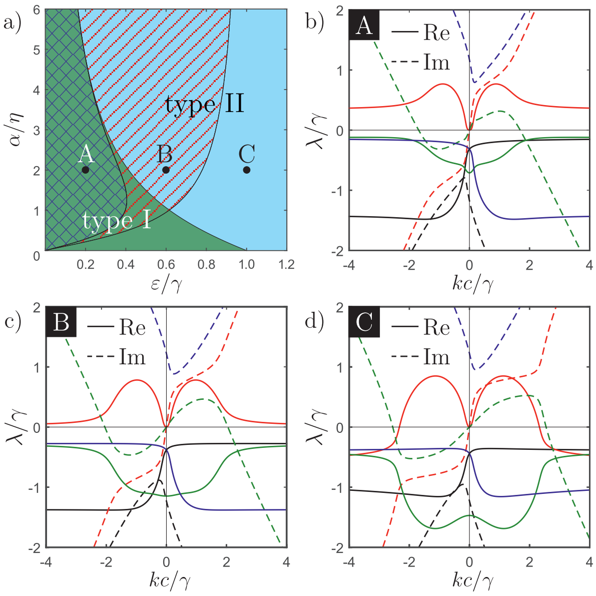

Figure 1: a) Stability diagram. Type I and II transitions are shown with green and blue colors respectively. The area free of hatching corresponds to the stable current regime. (b-d) The Lyapunov spectra of condensate current solutions. Solid and dashed lines show the real and imaginary parts, respectively. Parameters correspond to the black dots in the panel (a). The pumping power is slightly above the critical point.

The spontaneous current can be stable with respect to short wavelength fluctuations, but there is still a region of positive Lyapunov exponents for small wave vectors, as it is seen from Fig. 1(d). A condensate in a long enough microcavity chain thus falls apart and is expected to transform into a polariton current domain structure. On the other hand, a finite system with periodic boundary conditions, such as a microcavity ring chain, may support a global bifurcation towards a polariton condensate with spontaneously chosen and persistent circular current. This is possible in the case of short wavelength stability in a range of low pumping powers. The upper boundary of this range is determined by the cut-off fluctuation wave vector k_c defined by $\mathrm{Re}\lambda(k_c) = 0$ [see red curve in Fig. 1(d)]. The persistent current is possible in the ring with radius $R < k_c^{-1}$.

In summary, we considered polariton condensation in microcavities with potential and decay rate periodically modulated in space. Our analysis suggests that such systems undergo a spontaneous symmetry breaking and the formation of polariton currents. We identify the critical conditions for this effect to emerge and produce the phase diagram showing type I and type II transition boundaries. For large systems oscillating domains of counterpropagating currents are predicted. For systems smaller than the characteristic domain size, e.g., polariton rings, the spontaneously formed currents are stable and survive in the presence of spatiotemporal noise.

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2.16 Mechanically induced thermal breakdown in magnetic shuttle structures

O.A. Ilinskaya, S.I. Kulinich, I.V. Krive,
R.I. Shekhter, H.C. Park, M. Jonson

The study described below is part of the activity of the Advanced Study Group "Spin-Active Electric Weak Links", which is focused on exploring the role of electronic spin in heat transport properties of nanodevices [1]. We have shown that a coupling of electronic spin to nano-mechanical vibrations in magnetic shuttle devices, comprising a movable metallic grain suspended between two magnetic leads, affects qualitatively thermal transport through the device, providing mechanical assistance to heat transport through the device. An instability with respect to the onset of pronounced thermally induced mechanical vibrations of the grain was shown to occur if a magnetic field is applied to the device offering a new mechanism of spin-induced thermal breakdown. Heat transport in nanostructures is currently the subject of enhanced interest [2], especially due to the importance of heat removal from devices on the nanometer length scale. Electrically induced mechanical shuttling of electrons results in an exponential decrease of electric resistance (electric breakdown) [3] and this new type of electric conductance also significantly affects heat transport through a device. An intriguing question occurring in this context is whether or not similar shuttle instability can be induced thermally when there is no bias voltage applied to the device. In other words, is there room for a mechanically induced thermal breakdown in nano-electromechanical shuttle devices? Below we give a positive answer to this question.

The model we use to study a thermally driven magnetic shuttle is sketched in Fig. 1. It is the standard shuttle device (see, e.g., Refs. [4] and [5]), the only difference being that a temperature drop δT is applied to the leads instead of an electrical bias voltage and that one is interested in the heat flow J_q in response to this temperature drop δT. The thermal resistance R_T can be defined in analogy with the electrical resistance as $R_T = \delta T/J_q$. An exponential decrease in thermal resistance (thermal breakdown) is possible due to a transduction of thermal energy into the mechanical energy stored in the shuttle vibrations.

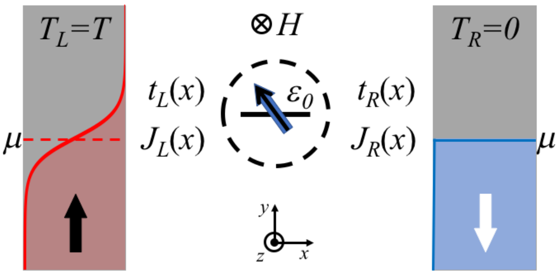

Figure 1: Sketch of the nanomagnetic device studied: a movable spin-degenerate single-level (with energy ε_0) quantum dot is tunnel coupled to two fully spin-polarized ferromagnetic leads. An external magnetic field H induces flips between the spin-up and spin-down states on the dot.

The tunneling of electrons between the dot and leads is described by the standard tunneling Hamiltonian

$$\hat{H}_t = t_L(x)\sum_k c^\dagger_\uparrow a_{k,L} + t_R(x)\sum_k c^\dagger_\downarrow a_{k,R} + \text{H.c.}. \tag{1}$$

The quantum description of the electron subsystem is given in terms of density matrix $\hat{\rho}_d$. The equation for the later is found using the tunneling Hamiltonian (4) as a perturbation. Keeping terms up to second order in the tunneling amplitude one gets a system of equations for the density matrix elementsρ_0, $\rho_{\uparrow(\downarrow)}$, $\rho_{\uparrow\downarrow}$, which are respectively the probabilities to find the dot to be unoccupied, singly occupied with spin a "up" ("down") electron, and the non-diagonal single-occupation matrix elements. We consider the limit of a strong Coulomb blockade ($U \to \infty$) neglecting double occupation of the dot. The mechanical equation of motion is found to be:

$$\frac{\partial^2 x}{\partial t^2} + \omega^2 x = -\frac{\alpha}{2m}\left(\rho_\uparrow - \rho_\downarrow\right), \qquad (2)$$

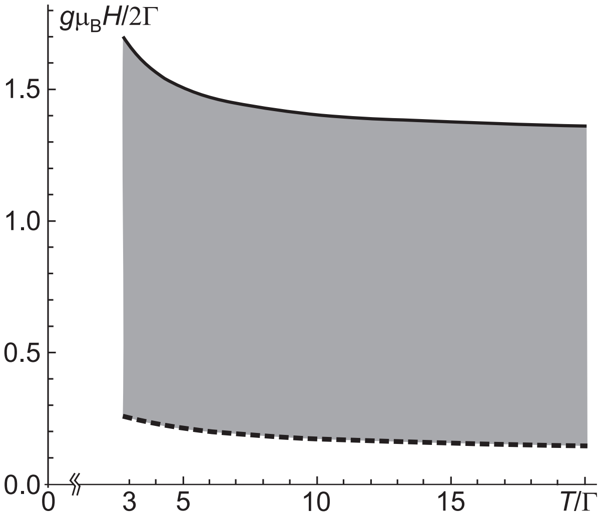

Figure 2: The lower (H_{c1}, dashed curve) and upper (H_{c2}, full curve) threshold magnetic fields plotted as functions of normalized temperature, T/Γ, for $\delta\varepsilon/\Gamma = 2$ in the adiabatic regime, $\omega \ll \Gamma/\hbar$. γ_0.

The probabilities for the "spin-up" and "spin-down" states on the dot to be occupied are nonlinear and temporally non-local functions of the displacement of the dot, $x(t)$. The instability with respect to the onset of mechanical vibrations can be analyzed by using a linear expansion in $x(t)$ of the equations for the density matrix and by using the adiabatic approximation $\omega = \Gamma$, where Γ is the tunneling width of the energy level of the non-vibrating dot. Our analysis [1] shows that the electromechanical coupling in the above limit results in a (small) additive renormalization of the vibration frequency ω and the appearance of a damping (or pumping) term $\gamma\dot{x}$ in the equation of motion (5). The coefficient $\gamma(\Gamma, H)$ is a function of the tunneling width and the magnetic field strength. The solution of Eq. (5) is a damped harmonic vibration $x = x_0 exp(i\omega t - \gamma t)$. The possibility to pump electronic energy into the mechanical vibrations occurs if $\gamma(\Gamma, H) < 0$. We have shown that an external magnetic field, oriented perpendicular to the magnetizations in the leads is able to invert the usual damping of mechanical vibrations into pumping regime if the strength of the magnetic field falls in a certain interval of values. Using the asymptotic behavior of $\gamma = \gamma(\Gamma, H)$ at low and high magnetic fields one finds:

$$\gamma \approx \gamma_1 \left[\left(\frac{H}{H_{c1}}\right)^2 - 1\right], \quad H \ll \Gamma/\mu_B$$
$$\gamma \approx \gamma_2 \left[1 - \left(\frac{H}{H_{c2}}\right)^2\right], \quad H \geq \Gamma/\mu_B \qquad (3)$$

where $H_{c1(2)} = \Gamma/g\mu_B$ and $H_{c2}/c1 = constant > 1$. A mechanical instability, resulting in an exponential growth of the amplitude of shuttle vibrations, occurs if the strength of the external magnetic field lies in the interval $[H_{c1}, H_{c2}]$. The pronounced mechanically facilitated transportation of "hot" electrons from the left- to the right lead induces an exponential growth of the thermal transport through the device, which we call a spin-induced thermal breakdown. The phase diagram of the latter is shown in Fig. 2 were the grey area corresponds to values of H and T where a breakdown is triggered.

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2.17 Signatures of many-body localization in steady states of open quantum systems

I. Vakulchyk, I. Yusipov, M. Ivanchenko, S. Flach, S. Denisov

Our paper [1] addresses footprints of many-body localization (MBL) leaves in open quantum systems, i.e., systems which are subjected to action from outside [2]. MBL [3], an extension of the fundamental concept of Anderson localization [4] into the world of interacting many-body systems, is attracting a growing interest in both theoretical and experimental communities. There is a series of recent experiments exploring MBL effects with ultra-cold atoms [5]. Very recently, MBL regimes were explored by using 'quantum chips', real-life superconducting quantum processors [6] used in quantum computers.

These technological advances posed a question of the fate of MBL not *in silico* (in an ideal 'world' of theoretical models and numerical simulations) but *in vitro*, when the interaction of a system with its environment is unavoidable. This question was addressed recently in a series of papers, where the action of the environment was modeled with the most severe type of decohrence, so called 'dephasing'. The obtained results fit the intuition: dephasing eventually destroys localization so that the asymptotic states of the systems with MBL Hamiltonians bear no signatures of localization.

In fact, the ultimate fate is plain: dephasing, whatever small, grinds any system – with or without many-body interactions, governed by an MBL or ergodic Hamiltonian – into maximally mixed state, when the system is uniformly 'smeared' over all possible eigenstates of its Hamiltonian, with no interference effects between different eigenstates. The asymptotic state cannot be changed by modifying the system Hamiltonian since the identity (which is the density operator corresponding to infinite temperature state) commutes with any Hamiltonian.

Is that all? In our paper we show that, by introducing into MBL systems, already subjected to dephasing, a special but physically relevant type of dissipation (already discussed in the literature), we can drive such systems into new asymptotic states bearing detectable signatures of localization. These signatures can be revealed by analyzing experimentally accessible characteristics, such as, e.g., the population imbalance, and more fundamental, theoretically relevant, qauntifiers as operator entanglement entropy. We also reveal connections between the state of an open many-body model in/out of the MBL regime and the spectral charactersitics of the corresponding density matrix thus establishing link between effects of localization and dissiaptive quantum chaos [7]; see figure.

Our findings are relevant in the context of the recent MBL studies by using quantum chips [6]. Namely, if one allows to superconducting quantum processor, beforehand set into MBL regime and subjected to special synthetic dissipation (discussed in our paper), equilibrate to its environment, then it would be possible to detect such features as population imbalance and thus quantify the amount of localization survived in the processor.

Future studies can also consider incorporation of the disorder into synthetic dissipation and, ultimately, a possibility to create MBL states by dissipative means solely. Such 'disordered' dissipation acquires a special relevance in the context of recent experiments with dissipatively coupled exciton - polariton condensate arrays [8].

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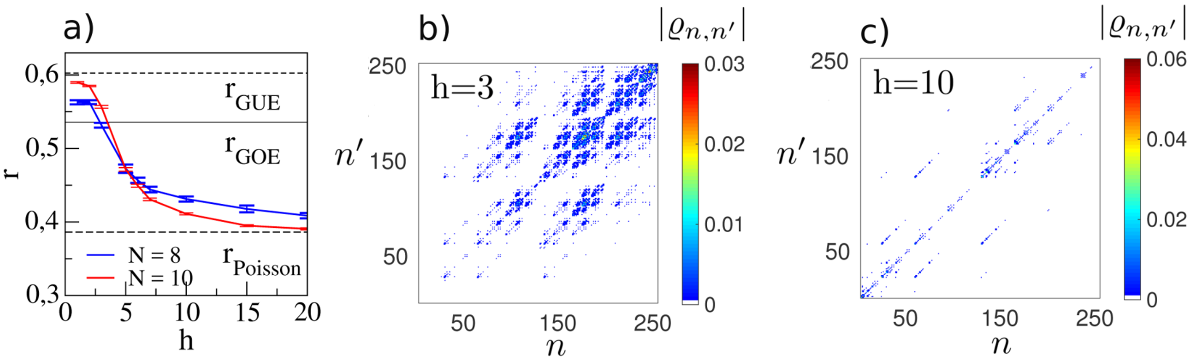

Figure 1: (a) Averaged ratio of consecutive level spacing of the steady state density matrix as a function of disorder strength h. Dashed line indicate values corresponding to different ensembels of randim matrices. (b-c) Absolute values of the elements of the steady state density matrix for different strengths of disorder h, before (b) and after (c) MBL transition.

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2.18 Stability of a topological insulator: Interactions, disorder, and parity of Kramers doublets

V. Kagalovsky, A.L. Chudnovskiy, I.V. Yurkevich

Topological insulators (TIs) have attracted a great deal of attention in condensed matter physics [1, 2]. The distinguishing feature of TIs is the existence of conducting edge states (Kramers doublets (KDs)) protected by time-reversal symmetry against localization by random potential. This robustness to disorder makes topological insulators to promising candidates for realization of topological quantum computations. Since conducting edge states are expected to play the major role in the quantum information transfer, the number of conducting edge channels becomes a crucial issue for practical application of in TIs. If there is an even number of Kramers doublets in clean system, they become pairwise localized by random potential, and the corresponding disordered system turns out to be an ordinary insulator. Till recently, there was the general believe based on the symmetry arguments, that a clean TI with an odd number of Kramers doublets can keep any odd number of conducting edge states in presence of disorder [3].

In this paper, we addressed the influence of interactions on the stability of the edge with an arbitrary number N of KDs against localization by disorder. Our main result is that an interacting system with N Kramers doublets at the edge may be either a trivial insulator or a topological insulator for $N = 1$ or 2, depending on the density-density repulsion parameters, whereas for $N > 2$ all KDs get fully localized by disorder pinning, irrespective of the parity issue. Assuming a realistic situation that all KDs exist within a layer which is narrower than a screening radius, we apply a model of a featureless (Coulomb-blockade or "orthodox" model) interaction between them. We show that for generic interaction parameters the charge density wave (CDW) instability of repulsive fermions in a clean (translation-invariant) system leads to the formation of a rigid structure (similar to the Wigner crystal in higher dimensions) stemming from the freezing of $(N-1)$ edge modes. The remaining single conducting mode describes the sliding of the total charge. For $N > 2$ it gets pinned by a backscattering term generated by a random inhomogeneity, leading to a full localization of the edge modes. The conductance is not fully suppressed by disorder in two situations only. In the case of a single Kramers doublet, $N = 1$, no gaps in the energy spectrum of edge states can be generated due to interaction, and the dimensionless edge conductance may be equal to one for a wide range of parameters. A pair of doublets, $N = 2$, also may survive the pinning by disorder (maintaining a dimensionless edge conductance equal to two), the stability region is small though, hence it is difficult to reach and observe experimentally.

Our conclusions are based on the analysis of perturbations of a clean system induced by disorder scattering and renormalized by interactions. Calculating the renormalization group (RG) scaling dimensions of operators, we sorted out the relevant perturbations that open gaps in the energy spectrum of edge states. The corresponding transport channels become suppressed at energies (given by temperature or applied voltage) below the gap.

The clean edge is described as a multichannel Luttunger liquid with equal intra- and interchannel interactions. Employing the bosonization technique, the Lagrangian of the system can be writted as

$$\mathcal{L} = \frac{1}{8\pi}\mathbf{\Psi}^T\left[\hat{\tau}_1\partial_t + \hat{V}\partial_x\right]\partial_x\mathbf{\Psi}, \tag{1}$$

where $\mathbf{\Psi}^T = (\phi^T, \theta^T)$ combines two mutually dual bosonic vector fields $\phi^T = (\phi_1, ..., \phi_N)$ and $\theta^T = (\theta_1, ..., \theta_N)$, parametrizing the charge density excitations $\rho_i = \partial_x\phi_i/2\pi$ and the current density excitations $j_i = \partial_x\theta_i/2\pi$ $(1 \le i \le N)$. The interactions are described by a block-diagonal matrix $\hat{V} = \mathrm{diag}\left(\hat{V}_+, \hat{V}_-\right)$ with $\hat{V}_+$ describing the density-density, and $\hat{V}_-$ describing the current-current interactions. Matrix elements of each block are given by the intra- and inter-channel couplings between the chiral bosonic modes. According to the standard nomenclature, we denote the intra- and inter-channel couplings between the modes propagating in the same direction as g_4 and g_4', and the interactions between the modes propagating in the opposite directions as g_2 and g_2' respectively. The matrix elements entering the Lagrangian Eq. (1) are given by $V_{\pm}^{ij} = (1 + g_{\pm})\delta_{ij} + g_{\pm}'(1 - \delta_{ij})$, where $g_{\pm} = g_4 \pm g_2$, and $g_{\pm}' = g_4' \pm g_2'$. An operator, describing multi-particle interaction beyond the forward scattering approximation, can be written in the most general form as $h(\mathbf{j}, \mathbf{q})e^{i(\mathbf{j}\phi+\mathbf{q}\theta)}$, where $\mathbf{j}$ and $\mathbf{q}$ are N-component vectors which components q_i and j_i can take integer or half-integer values. The vector $\mathbf{q}$ is restricted by the charge neutrality requirement $\sum_{i=1}^{N} q_i = 0$. Moreover, in the clean system, all interactions conserve the total momentum, which imposes the condition $\sum_{i=1}^{N} j_i = 0$. The consequences of momentum conservation can be made mathematically explicit by introducing the "center-of-mass" fields $\Phi = \frac{1}{\sqrt{N}}\sum_{i=1}^{N}\phi_i$ and $\Theta = \frac{1}{\sqrt{N}}\sum_{i=1}^{N}\theta_i$, and the fields describing the fluctuations orthogonal to the "center-of-mass" coordinate, resulting in the decomposition $\boldsymbol{\phi} = \Phi\mathbf{e} + \boldsymbol{\phi}_{\perp}$, and analogously for $\boldsymbol{\theta}$. The momentum conservation implies that the center-of-mass fields Φ and Θ are not affected by interactions in the clean system. Analysis of scaling dimensions of the allowed operators shows that all orthogonal modes $\boldsymbol{\phi}_{\perp}$ become frozen by interaction even in the clean system, resulting either in the charge-density wave or in the superconducting instability. The center-of-mass mode remains soft. In the case of charge-density-wave ordering, it describes a sliding Wigner crystal. Its dynamics is governed by the Luttinger liquid Lagrangian with the effective Luttinger parameter $K_{\parallel}$, which is given by

$$K_{\parallel} = K\sqrt{(1 + (N-1)\alpha_-)/(1 + (N-1)\alpha_+)} \tag{2}$$

with $\alpha_{\pm} = g_{\pm}'/(1 + g_{\pm})$, and K being the Luttinger liquid parameter in the absence of interchannel couplings. For the commonly accepted model that includes only density-density interactions ($\alpha_- = 0$) we found that the region of the existence of a delocalized (conducting) center-of-mass mode for repulsive electrons, $K < 1$, is determined by the inequalities

$$(3N/8)\left[1 + (N-1)\alpha_+\right]^{1/2} < K < (1 - \alpha_+)^{1/2}. \tag{3}$$

In Fig. 1 we show regions of stability for systems with $N = 1$ and $N = 2$ KDs. For a single KD ($N = 1$) there is no interchannel interaction hence one should put $\alpha_+ = 0$. A single conducting state even for a system with a pair of KDs (N = 2) survives pinning only in a small region of interaction parameters (see Fig. 1). Furthermore, it is clear, that the inequalities Eq. (3) have no solution for $N > 2$. Therefore we conclude, that *more than two ($N > 2$) interacting Kramers doublets are pinned by disorder for any inter- and intra-channel interaction strengths.*

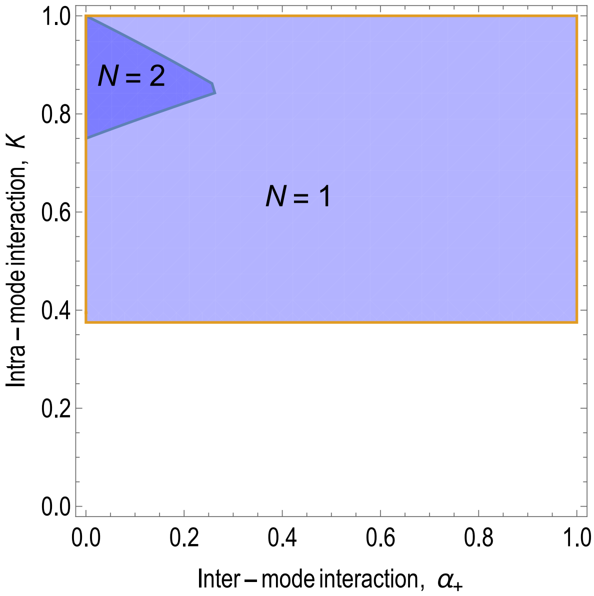

Figure 1: The phase diagram for a set of N Kramers doublets under a repulsive density-density interaction. The only two stable states, $N = 1$ and $N = 2$, are shown by light and dark blue regions, correspondingly.

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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 2017 and 2018, 127 scientists from over 30 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 2017 and 2018, a total of 424 external workshop participants attended our 9 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

- *Attosecond Physics at the Nanoscale*
  International Workshop: October 29 – November 2, 2018
  Scientific coordinators: M. Ciappina, S. Kim, Y.-J. Kim
  66 participants from 15 countries (including 29 participants from Korea)
- *Disordered Systems: From Localization to Thermalization and Topology*
  International Workshop: September 3 – 7, 2018
  Scientific coordinators: R. Roemer, L. Santos, K.-S. Kim
  56 participants from 14 countries (including 27 participants from Korea)
- *Quantum Information and Correlation in Quantum Dots*
  International Workshop: August 13 – 17, 2018
  Scientific coordinators: Y. Chung, Y.-J. Doh, H.-S. Sim
  Local scientific organizers: D. Kim, H.C. Park
  68 participants from 11 countries (including 50 participants from Korea)
- *Edge Reconstruction: Transport and Quantum Phase Transitions*
  International Workshop: June 25 – 29, 2018
  Scientific coordinators: V. Kagalovsky, I. Lerner, I. Yurkevich
  53 participants from 12 countries (including 15 participants from Korea)
- *Meta-Optics and Metamaterials*
  International Workshop: April 23 – 27, 2018
  Scientific coordinators: Y. Kivshar, Q-H. Park, H.-J. Lee
  Local scientific organizers: J.-H. Kang, B. Min
  60 participants from 6 countries (including 52 participants from Korea)
- *Dissipative Quantum Chaos: from Semi-Groups to QED Experiments*
  International Workshop: October 23 – 27, 2017

Scientific coordinators: S. Denisov, I. Lesanovsky, R. Fazio
55 participants from 12 countries (including 28 participants from Korea)

- *Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems*
  International Workshop: September 18 – 22, 2017
  Scientific coordinators: A. Akbari, I. Eremin, T. Tohyama
  65 participants from 13 countries (including 32 participants from Korea)
- *Flatband Networks in Condensed Matter and Photonics*
  International Workshop: August 28 – September 1, 2017
  Scientific coordinators: O. Derzhko, S. Flach, J. Richter
  57 participants from 20 countries (including 20 participants from Korea)
- *Physics of Exciton-Polaritons in Artificial Lattices*
  International Workshop: May 15 – 19, 2017
  Scientific coordinators: Y. Rubo, T. Liew, I. Savenko
  40 participants from 14 countries (including 7 participants from Korea)

Future overview

- *Spintronics and Valleytronics of Two-dimensional Materials*
  International Workshop: May 20 – 24, 2019
  Scientific coordinators: M. Glazov, S. Höfling, I. Savenko
- *Recent Advances in Topological Photonics*
  International Workshop: June 17 – 21, 2019
  Scientific coordinators: D. Leykam, Z. Chen, A. Szameit
- *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, K.-S. Kim
- *Frustrated Magnetism*
  International Workshop: October 14 – 18, 2019
  Scientific coordinators: A. Andreanov, Y.B. Kim, S.B. Lee

3.1.2 Advanced Study Groups

- *Spin-Active Electric Weak Links*
  Advanced Study Group: Mar. 10 – Apr. 10, Aug. 12 – Sep. 12, Nov. 15 – Dec. 15, 2018
  Convener: R. Shekhter (University of Gothenburg, Sweden)
  Members: A. Aharony, O. Entin-Wohlman, M. Jonson, I. Krive, H.C. Park, D. Radić, J. Suh
- *Edge Reconstruction in Quantum Hall Systems and Topological Insulators*
  Advanced Study Group: June 18 - July 13, 2018
  Convener: I. Yurkevich (Aston University, UK)
  Members: D. Gangardt, Y. Gefen, M. Goldstein, V. Kagalovsky, U. Khanna, K.-S. Kim, I. Lerner, Y. Meir, J. Park, V. Yudson
- *Topological Phases in Arrays of Luttinger Liquid Wires*
  Advanced Study Group: August 28 - September 27, 2017
  Conveners: A. Chudnovskiy (University of Hamburg, Germany)
  Members: V. Kagalovsky, I. Yurkevich, F. Kusmartsev

- *Dissipative Quantum Chaos*
  Advanced Study Group: February, August, October 2017
  Convener: S. Denisov (University of Augsburg, Germany)
  Members: B. Altshuler, M. Ivanchenko, S. Diehl, A. Eckardt, D. Poletti

Future overview

- *Functional Spin-Active Mesoscopic Weak Links*
  Advanced Study Group: Jan. 27 – Feb. 27, Aug. 5 – Sep. 12, 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

3.1.3 Workshop Reports

Attosecond Physics at the Nanoscale
Scientific coordinators: Marcelo Ciappina, Seungchul Kim, Young-Jin Kim

Recently two emerging areas of research, attosecond and nanoscale physics, have started to come together. Attosecond physics deals with phenomena occurring when ultrashort and intense laser pulses, with duration on the femto- and subfemtosecond time scales, interact with atoms, molecules or solid-state matter. On the other hand, nanoscale physics involves the manipulation and engineering of mesoscopic systems, such as solids, metals and dielectrics, with nanometric precision. Although nano-engineering is a vast and well-established research field on its own, the merge with intense laser physics is relatively recent. The combination of attosecond time resolution, joint with nanoengineering, paves the way to groundbreaking discoveries. For instance, the development of light-controlled transistors, with switching speeds several orders of magnitude larger than the actual electronic ones, appears as a certain prospect in the horizon. There are, however, several theoretical and experimental barriers still to be demolished.

The aim of this Workshop was then to gather theoretical and experimental experts both in attosecond science and nanoscale physics and establish a genuine and open discussion environment. The International Workshop “Attosecond Physics at the Nanoscale” was held at the Center for Theoretical Physics of Complex Systems (PCS) from the October 29th, 2018, until November 2nd, 2018. The workshop attracted around 70 participants, including 34 speakers between invited and contributed ones. All of the speakers work in leading groups in Korea, Europe, USA and Asia. Their area of expertise cover a broad range of both attosecond and nanoscale physics, namely ultrafast optics, high-order harmonic generation in atoms, molecules, liquids and solids, quantum control, x-ray science, numerical multiscale modeling of strong laser field phenomena, plasmonics, laser-assisted processes, amongst others.

The workshop started with the opening address given by Prof. Sergej Flach, Director of PCS IBS, joint with a brief overview about the relevance of Atto-nano Physics by Dr. Marcelo Ciappina, one of the Scientific Coordinators. Soon afterwards a total of 34 talks, including invited and contributed ones, and 3 contributed poster presentations were given. A diverse set of topics were discussed during the workshop including:

- Intra- and interband transitions in high-order harmonic generation from solids (XueBin Bian)
- Selection rules and their applications in high harmonic generation (Oren Cohen)
- Attosecond quantum path interferences (Amelle Zaïr)

- Extreme ultraviolet high harmonic spectroscopy of condensed matter (Tran Trung Luu)
- Analysis of the defocusing-assisted phase matching in extended high harmonic generation (Cheng Jin)
- High-order harmonic generation in solids (Liang-You Peng)
- Photoemission from solid surfaces and nanoparticles with attosecond- nanometer spatiotemporal resolution (Uwe Thumm)
- Nanoscale control of high-harmonic generation from crystals (Giulio Vampa)
- Strong field driven electron and spin dynamics (Martin Schultze)
- Multi-scale simulation of high harmonic generation in condensed matter (Isabella Floss)
- Attosecond dispersive soft X-ray absorption fine structure spectroscopy in semi-metals (Themistoklis Sidiropoulos)
- Towards molecular fieldoscopy (Hanieh Fattahi)
- Waveform-controlled electron acceleration with near fields: clusters vs. tips (Thomas Fennel)
- Attosecond probing of nanoplasmonic fields (Michael Krüger)
- Nanooptical near-field probing with ultrafast photoemission (Péter Dombi)

The most important aspect to highlight from the Workshop is the superior quality of the presentations and the exceptional discussion environment that took place. Additionally, several speakers presented unpublished data, what is not a common practice. There was plenty of time for open talks and certainly several collaborations will be initiated as a fruit of them.

As the meeting has brought together both theoretical and experimental experts in a broad range of fields, it seems clear that this synergy will open new and fundamental areas of research. Additionally, it will certainly boost the development of new directions in the field of atto-nano physics, that will lead to pioneering discoveries in the years to come.

Disordered Systems: From Localization to Thermalization and Topology

Scientific coordinators: Rudolf Roemer, Lea Santos, Ki-Seok Kim

The "International Workshop on Disordered Systems" (IWDS2018) gathered 53 experts and young researchers in different fields where disorder plays a fundamental role at the IBS Center for Theoretical Physics of Complex Systems (PCS IBS), Daejeon, during September 3 – 7, 2018. Participants came from Asia (34), Americas (11), and Europe (8). In total, there were 53 participants, 26 talks and 5 posters. The scientific topics covered were:

- Transport and localization in disordered systems
- Thermalization and many-body localization
- Quantum dynamics in many-body systems
- Topological phases of matter and their properties

The workshop provided a stimulating and motivating scientific atmosphere to learn about the most recent advances in the field and to foster further collaborations between the participants. Although the programme of the workshop contained many talks, there was still good time for the participants to discuss, exchange information, and conduct some research. The workshop was particularly useful in introducing the emerging Asian community of disordered systems researchers to the state of the field and to showcase their talents to the international experts. The workshop also included a poster prize, awarded and sponsored by Physica E – low-dimensional systems and nano-structures, and judged by three invited speakers.

The workshop overall succeeded in providing a platform to discuss the physics of many-body localization, thermalization and topology to an audience of experts in traditionally mainly single-particle localization physics. It is clear that the role of interactions will become ever more important in the future of the field. Nevertheless, it was also clear how the many approaches developed in single-particle localization physics now provide a very fruitful basis for these currently ongoing many-body developments.

A particular highlight of the workshop was the outreach into other areas of physics where quantum interference and many-body aspects are important. Here we just wish to point to talks on superconductivity, machine learning, scanning gate techniques, renormalization groups, glasses and transport in complex electric power grids. This diversity highlights the uniquely successful appeal of the field to other areas of physics. A considerable part of the conference was also given to applications of classical waves such as microwaves and light where localization physics provides an area of application while still retaining many open questions of fundamental importance.

Looking into the future, it is clear that the workshop participants were hoping that the workshop series will continue. At the meeting, two proposals for holding the next event emerged and at present this is scheduled to take place in 2020 at Morelia in Mexico. While it is still a bit too early to discuss specifics, it is already clear that the workshop's tradition to reach out to exciting and new topical areas of the field will continue in 2020 as well.

We should also mention that this workshop had a very good number of female participants, with 6 talks given by women. A very nice outcome of this gathering was that some of these women are now trying to collaborate among them and will be visiting each other already during this year. A suggestion for the future could be to explicitly ask organizers to try to make sure their workshops have a certain minimum number of female participants, such as at least 15-25%.

Feedback from the participants, on the high quality of the premises, the hotel accommodation and the workshop excursion, was unanimously very positive. The overall organization of the event, before and during IWDS, was of excellent quality. As scientific organizers, we did not receive a single negative comment from a participant regarding any organisational matter.

We thank the PCS IBS for making possible this very successful event.

Quantum Information and Correlation in Quantum Dots

Scientific coordinators: Yunchul Chung, Yong-Joo Doh, Heung-Sun Sim
Local scientific organizers: Dohun Kim, Hee Chul Park

The International Workshop "Quantum Information and Correlation in Quantum Dots" took place at the IBS Center for Theoretical Physics of Complex Systems (PCS), Daejeon on August 13 – 17, 2018. It was organized and funded by the PCS IBS. It was scientifically coordinated by the Mesoscopic Physics Society of Korea and the SRC Center for Quantum Coherence in Condensed Matter. The coordinators are Yunchul Chung (Pusan National University, Korea; Mesoscopic Society; SRC Center), Yong-Joo Doh (GIST, Korea; Mesoscopic Society; SRC Center), Dohun Kim (Seoul National University, Korea; Mesoscopic Society), Hee Chul Park (PCS IBS, Korea; Mesoscopic Society), and Heung-Sun Sim (KAIST, Korea; Mesoscopic Society; SRC Center).

During the workshop, there were 25 invited talks, 3 contributed talks, and 8 posters on the topics of:

- Qubits and quantum information processing based on quantum dots
- Quantum impurities and multichannel Kondo effects
- Solid-state platforms for topological anyons including Majorana fermions
- Engineering many-body states in multiple quantum dots
- Quantum electron transport in topological matters

The talks covered recent experimental and theoretical efforts towards quantum information and quantum simulation based on quantum dots, topological qubits and topological quantum computing, exotic quantum impurity problems, and quantum coherence in topological matters. The workshop promoted scientific discussion, information exchange, and collaborations among the participants and the members of the PCS IBS; we thank the research groups "Quantum Many-Body Interactions and Transport" and "Light-Matter Interaction in Nanostructures" of the PCS IBS for their active contribution to the workshop. We believe that the workshop helped formulating many exciting new ideas and directions of mesoscopic physics, quantum technology, and exotic non-Abelian particles.

It is our delight that the workshop participants enjoyed much the talks and the organization. We appreciate the assistance by the administrators of PCS IBS, Dr. Dominika Konikowska, Ms. Gileun Lee, and Ms. Heeyun Lee.

Edge Reconstruction: Transport and Quantum Phase Transitions

Scientific coordinators: Victor Kagalovsky, Igor Lerner, Igor Yurkevich

The International Workshop "Edge reconstruction: Transport and Quantum Phase Transitions", coordinated by Victor Kagalovsky (Shamoon College of Engineering, Israel), Igor Lerner (University of Birmingham, UK), Igor Yurkevich (Aston University, UK), was held at the IBS Center for Theoretical Physics of Complex Systems, Daejeon, South Korea on June 25 – 29, 2018.

During this week, there have been 29 invited talks and 6 posters on the subject of edge reconstruction and topics relevant to the Workshop subject. The Workshop has demonstrated enormous interest of Condensed Matter community in the edge reconstruction in Fractional Quantum Hall systems and phase transition that occur at the edge.

Among the speakers there were leading experts in the field of the edge physics, topological insulators and phase transitions. We will mention just few very good talks presented at our Workshop (combined in the groups of close subjects):

- Alexander Mirlin, Igor Gornyi, and Dmitry Polyakov – transport and noise in the fractional (filling factor = 2/3) quantum Hall edge; fermionic description of the edge leading to a fermionic kinetic equation; energy spectroscopy on the edge of an integer QH state, detecting various electron-electron inelastic scattering processes.
- Stefan Fischer, Thomas Ihn, and Klaus Ensslin – energy spectroscopy on the edge of an integer QH state, distinguishing between elastic and inelastic processes.
- Jukka Vaeyrynen and Moshe Goldstein – the possibility of emerging superconductivity in reconstructed edges.
- Ganpathy Murthy, Sumathi Rao, and Efrat Shimshoni – possible goldstone modes at the edge of graphene in the QH regime.
- David Saad and Tomi Ohtsuki – machine learning and its application to condensed matter.

We believe that the workshop helped establishing the directions of further development in the emerging theory of edge reconstruction in quantum Hall systems. Many problems were discussed and many new ideas were formulated during numerous discussions between participants. This became possible due to the friendly environment of the Center and perfectly designed schedule of the Workshop that left plenty of time for after-talk discussions (10-minut slots were allocated for that reason) and a reasonable break between morning and evening sessions. What is important that members of the Center were also involved in the work of the workshop, on the level of informal scientific discussions.

We are very thankful to the PCS IBS its generous support of the workshop. We are grateful to the local organizers, Dr. Dominika Konikowska, Ms. Gileun Lee and Ms. Heeyun Lee, for their efforts and help that made this workshop a perfectly organized scientific event.

Meta-Optics and Metamaterials
Scientific coordinators: Yuri Kivshar, Q-Han Park, Hak-Joo Lee
Local scientific organizers: Ji-Hun Kang, Bumki Min

With a growth of research interest in the resonant light-matter interaction in subwavelength photonic structures, metamaterials have been providing a useful avenue for implementing revolutionary concepts of light manipulation in sub-wavelength regimes. Further advances of meta-optics and metamaterials require novel breakthrough by merging different interdisciplinary approaches and directions such as nonlinear optics, topological photonics, and quantum physics.

In order to incorporate most recent advances of innovative theoretical and experimental approaches in exploring subwavelength optics in metamaterials, the International Workshop on Meta-Optics and Metamaterials was held at the IBS Center for Theoretical Physics of Complex Systems (PCS) on April 23 – 27, 2018. The workshop attracted more than 60 participants, including 20 invited speakers from leading groups in Korea, USA, Europe, and Asia, in different areas of metamaterial and nanoscale physics to explore the confluence of subwavelength photonics, metamaterials, metasurfaces, quantum physics, the physics of two-dimensional materials, and nonlinear optics.

The workshop started with the opening address given by Prof. Sergej Flach, Director of the PCS IBS, and 20 invited talks and 9 contributed poster presentations were given. The diverse topics discussed during the workshop included:

- Nanoplasmonics (Zee Hwan Kim, Myung-Ki Kim)
- Metamaterials with low-dimensional materials (Ji-Hun Kang, Chengwei Qiu, Nicolae Panoiu)
- Spatiotemporal metamaterials (Bumki Min, Andrea Alú)
- Nonlinear effects with metamaterials (Olivier Martin, Dai-Sik Kim, Nicolae Panoiu, Guixin Li)
- Non-local metamaterials and their novel properties (Q-Han Park)
- Chiral optical responses in metamaterials (Junsuk Rho)
- Optical metasurfaces (Young Chul Jun, Q-Han Park)
- Multifunctional, tunable metamaterials (Jonathan Schuller, Lei Zhou)
- Photonic spin-Hall effect (Lei Zhou)
- Soft matters in metamaterials (Seungwoo Lee)
- Quantum effects with metamaterials (Dai-Sik Kim, Jwa-Min Nam)
- Transformation optics and interface problems (Mikyoung Lim, Jung-Wan Ryu)
- Novel applications in biochemistry and information processing (Jwa-Min Nam, Tie Jun Cui)

Also, on April 24, Prof. Olivier Martin from EPFL, Switzerland, presented a colloquium talk entitled "Plasmonics: From materials to artificial colors and metasurfaces" for illustrating novel concepts of plasmonic metamaterials to broader audiences.

The important achievement in the workshop was incorporation of recent new developments in the physics of metamaterials, plasmonics, and quantum and nonlinear optics that facilitates new discoveries. Active interactions between the participants have been made in the welcome reception, discussion sessions, lunch breaks, and exceptionally long 30 minutes coffee breaks that allowed heated discussions and opened an avenue for the initiation of new collaborations.

As the workshop has brought intensive studies of new fundamental properties of light in sub-wavelength structured metamaterial systems, it will boost the development of new directions in the fields of nano-photonics, plasmonics, and metamaterials that will lead to ground-breaking discoveries in the coming years.

Dissipative Quantum Chaos: from Semi-Groups to QED Experiments

Scientific coordinators: Sergey Denisov, Igor Lesanovsky, Rosario Fazio

The international workshop "Dissipative Quantum Chaos: from Semi-Groups to QED Experiments" took place at the Center for Theoretical Physics of Complex Systems (PCS), Institute of Basic Science (IBS), in Daejeon, Republic of Korea, from October 23 till October 27, 2017. The workshop was coordinated by Sergey Denisov (University of Augsburg, Germany, and N.I.Lobachevsky State University of Nizhny Novgorod, Russia), Igor Lesanovsky (University of Nottingham, UK) and Rosario Fazio (ICTP & Scuola Normale Superiore, Italy). Participants contributed to the workshop with 21 invited talks, 4 short talks, and 7 posters. The goal of the five-day workshop was to to bring together theoreticians, working in the field of dissipative quantum mechanics (Lindblad generators, semi-groups, quantum Monte-Carlo methods etc.) and theoreticians/experimentalists dealing with quantum electro-dynamical (QED) and solid-state quantum systems, where dissipation and decoherence are parts of the lab reality.

On the first day of the workshop, Tomaž Prosen gave an opening talk on regular and chaotic non-equilibrium steady-state density operators; his talk set main 'ideological' lines and posed several important questions. For example, what does it mean for an open many-body quantum systems to be 'chaotic' (or 'regular')? Prosen's conjecture is that this property can be quantified by using spectral properties of the asymptotic density operator (when in the case of an isolated coherent system these properties are define in terms of the corresponding Hamiltonian). A related issue, spectral statistics of quantum maps and a (possible) demarcation of 'chaotic' and 'regular' maps, was addressed in the talk of Karol Życzkowski. These talks were contrasted by the talk of Eva-Maria Graefe on spectral statistics of PT-symmetric random matrix ensembles (an alternative way to bring 'irreversibility' into quantum dynamics). Victor Galitski presented a new generalization of the concept of Lyapunov exponents to quantum systems. More specific issues, such as fractal non-equilibrium steady states, were discussed by Marko Žnidarič, while Dariusz Chruściński discussed non-Markovian variants of quantum master equations. Chruściński's talk was complemented by the talk of Massimo Palma, who presented microscopic renewal processes resulting in non-Markovian master equitations.

The mean-field approach to dissipative quantum chaos was represented by the talks of Emil Yuzbashyan and Jonathan Keeling. Both referred to QED cavities where leaky photonic mode is coupled to a set of qubits (spins); the corresponding mean-field description can be obtained by tending the number of qubits to infinity. In this context, an intriguing question on genetic links between such basic concepts of classical nonlinear dynamics as synchronizations and bifurcations and quantum super-radiance phenomena naturally occur. Mikhail Fistul discussed an effect of ‘quantum synchronization’ in disordered arrays of interacting superconducting qubits.

Other interesting aspects of dissipative many-body quantum systems were covered by the talks of Beatriz Olmos Sanchez and Sebastian Diehl (topological properties of atomic gases and condensates) and Janne Ruostekoski (light propagation in atomic dipolar medium). Thermodynamical aspects of dissipative quantum dynamics far out of equilibrium were discussed by Mauro Paternostro (the role of quantum coherence in entropy production) and Juzar Thingna (impact of periodic modulations). André Eckardt told about an analogue of Bose condensation in driven-dissipative bosonic gases.

Finally, a very intriguing subject of many-body localization (and its footprints in open quantum systems) was discussed by Boris Altshuler, Dario Poletti, and Mikhail Ivanchenko.

We, the organizers, believe that the workshop established several lines for further development of the emerging theory of dissipative quantum chaos. Many problems were discussed and many new ideas were formulated during numerous after-hour discussions. This became possible due to the nice environment of the Center, its cozy atmosphere and charming discussion rooms. What is important that members of the Center were also involved in the work of the workshop, on the level of invited talks (Mikhail Fistul), poster sessions, and informal scientific discussions. Two young local researchers, Ivan Savenko (group leader) and Ihor Vakulchyk (Ph.D. student) were given a chance to present their results with short talks.

We are very thankful to the PCS IBS due to whose generous support the idea of the workshop was materialized. We are particularly grateful to the local organizers, Dr. Dominika Konikowska and Ms. Sol Cho, whose effort and professional care made this workshop a very efficient and perfectly organized scientific event.

Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems

Scientific coordinators: Alireza Akbari, Ilya Eremin, Takami Tohyama

The one-week international International Workshop “Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems” took place at the PCS IBS, as an inaugural workshop of the ICTP Asian Network on Condensed Matter and Complex Systems. The workshop was coordinated by Alireza Akbari (APCTP, Korea), Ilya Eremin (Ruhr-University Bochum, Germany), and Takami Tohyama (Tokyo University of Science, Japan). It focused on the topic of ultrafast dynamics and non-linear effects in strongly correlated systems ranging from Mott insulators to unconventional superconductors. As main goals, the meeting addressed the state of the art in experimental investigation and theoretical understanding of strongly excited states far from equilibrium and some of the most pressing controversies in this field of research.

More than 90 participants from Korea, Japan, Philippines, Vietnam, Thailand, Europe, and USA took part in this meeting. The program had 28 talks including 25 invited oral presentations, and three contributed talks, which were presented by the world-leading experts in the field who covered major recent advances in both theory and experiment. Besides, the younger participants presented their results in the form of 14 posters. The talks, discussions, and posters demonstrated that the field has great prospects, and participants presented new and interesting results and discussed their contribution in great details, which caused the meeting to be definitely a great success.

In conclusion, the workshop clearly responded to its main goals to bring together leading scientists working in the field of Short-time Dynamics to discuss the recent advances in these fields, and to visualize further research prospects and to promote new research collaborations, as well as, to bring together top level scientists and young researchers in order to stimulate lively interaction and exchange of ideas between them.

Two main results of the Workshop are (i) a focused exchange of ideas on the recent experimental and theoretical developments in the field of pump-probe spectroscopy in correlated electron systems, and (ii) an involvement of young scientists in the discussion which has stimulated new research collaborations.

Acknowledgements: We would like to thank the IBS Center for Theoretical Physics of Complex System (PCS) for its hospitality and excellent infrastructure provided for our participants. We are grateful to the IBS, APCTP and ICTP for their financial support. We would like to thank the team of secretaries at the IBS and APCTP, for their kind assistance and ever-friendly support in organizing the workshop. We are particularly grateful to acknowledge the local organizers: Dr. Dominika Konikowska, Ms. Sol Cho, and Ms. Heeyun Lee, whom they did the main part of works and without their helps we could not maintain our goals.

Flatband Networks in Condensed Matter and Photonics

Scientific coordinators: Oleg Derzhko, Sergej Flach, Johannes Richter

The International Workshop “Flatband Networks in Condensed Matter and Photonics” took place at the Center for Theoretical Physics of Complex Systems (PCS), Institute of Basic Science (IBS), in Daejeon, Republic of Korea, from August 28 till September 1, 2017. The workshop was coordinated by Oleg Derzhko (Institute for Condensed Matter Physics NASU, Ukraine), Sergej Flach (PCS IBS, Korea), and Johannes Richter (Otto-von-Guericke University Magdeburg, Germany). During these five days, there were 26 invited and 6 contributed talks as well as 14 posters on different aspects of flatband physics and related topics. The workshop demonstrated the growing interest of an enlarging research community of theoreticians and experimentalists in unexpected properties of various systems possessing completely dispersionless one-particle energies.

At the beginning, Prof. Andreas Mielke (University of Heidelberg, Germany) presented his reminiscences of emergence the interest in flatband systems in the late 80’s and discovery of flatband ferromagnetism of the Hubbard model. Another prominent event which occurred within the framework of the workshop was an enthusiastic colloquium talk by Prof. Alexander Szameit (University of Rostock, Germany) on topological photonics. Further talks touched specific problems related to flatband networks in solid state, photonics, for trapped cold-atom gases etc.

- General theoretical studies reported at the workshop include engineering and design of flatband networks (Alexei Andreanov, PCS IBS, Korea, and Ching Hua Lee, Institute of High Performance Computing, Singapore), emergence of flatbands (localized states) due to magnetic flux (Ricardo Dias, University of Aveiro, Portugal), interactions (Zsolt Gulácsi, University of Debrecen, Hungary, and Zhou Li, RIKEN, Japan), or in certain decorated lattices (Arunava Chakrabarti, University of Kalyani, India) and finite-size magnetic molecules (Jürgen Schnack, Bielefeld University, Germany), as well as non-Hermitian flatband models (Daniel Leykam, PCS IBS, Korea). Magnus Johansson (Linköping University, Sweden) reviewed a work on nonlinear localized modes in some lattices having linear flat bands. Electronic and hard-core-bosonic flatband systems in the presence of strong correlations (Hubbard, Kondo, etc.) have been addressed in the talks of Andreas Mielke (University of Heidelberg, Germany), Hosho Katsura (University of Tokyo, Japan), Akinori Tanaka (National Institute of

Technology, Ariake College, Japan), Minh-Tien Tran (Vietnam Academy of Science and Technology, Vietnam). Finally, Oleg Gendelman (Technion – Israel Institute of Technology, Israel) discussed the concept of flat bands for mechanical lattices, Pragya Shukla (Indian Institute of Technology Kharagpur, India) considered effects of weak disorder on the spectrum of flatband tight-binding Hamiltonians, and Mikhail Fistul (MISiS, Russia & PCS IBS, Korea) discussed thermodynamics and dynamics of a classical nonlinear Josephson junctions network supporting flatbands.

- Topological phenomena with flatband states have been highlighted in the talks of Emil Bergholtz (Stockholm University, Sweden), Päivi Törmä (Aalto University, Finland), Mykola Maksymenko (Institute for Condensed Matter Physics, NASU, Ukraine).
- Several talks were devoted to solid-state systems. They included discussions on dynamics of highly frustrated quantum magnets (Andreas Honecker, University of Cergy-Pontoise, France), pyrochlore spin liquids (Ludovic Jaubert, University of Bordeaux, France), spin-liquid regime in some spin-orbit coupled magnets (Ioannis Rousochatzakis, University of Minnesota, USA), ab initio study results for honeycomb-, kagome-lattice and some other geometrically frustrated materials (Maria-Roser Valentí, Goethe University Frankfurt, Germany, and Zheng Liu, Tsinghua University, China). Jozef Strečka (P.J.Šafárik University, Slovakia) explained how to use a flatband approach to examine an octahedral spin chain, and Taras Verkholyak (Institute for Condensed Matter Physics, NASU, Ukraine) used a concept of localized triplons with hard-core constraints to explain magnetization plateaux in the Shastry-Sutherland model. Finally, Hidekazu Tanaka (Tokyo Institute of Technology, Japan) presented his newest experimental data on dispersionless excitations and crystallization of triplons in dimerized quantum magnet Ba2CoSi2O6Cl2.
- Photonics and trapped cold-atom gases in optical lattices provide another playground for flatband physics. Sven Höfling (University of Würzburg, Germany) reported recent experimental and technological progress to tailor the properties of exciton-polaritons in arbitrary lattices. Sebabrata Mukherjee (Heriot-Watt University, UK) reported on experimental realizations of dispersionless states in photonic lattices formed by arrays of evanescently coupled optical waveguides. Dong-Hee Kim (GIST, Korea) gave a talk on cellular dynamical mean-field study of flatband magnetism of trapped Fermi gases in Lieb lattices. Effective theory in the flat bands of attractive Hubbard models addressed in the talk of Murad Tovmasyan (ETH Zurich, Switzerland) can be used to understand transport measurements in cold atom experiments.

The overall impression from the workshop is that the flatband systems exhibit a plethora of exotic features which deserve to be studied and which may have interesting applications. The workshop has demonstrated that this rapidly developing field is a realm of theoretical and experimental researches nowadays and new discoveries here are anticipated. Feedback from the different workshop participants was extremely positive. For those working on flatband physics, the PCS IBS is now seen as the place of choice for establishing new collaborations and the visibility of the local research done in this field has been further increased. Several researchers expressed a strong interest in working with PCS IBS in the future.

Physics of Exciton-Polaritons in Artificial Lattices

Scientific coordinators: Yuri Rubo, Timothy Liew, Ivan Savenko

The International Workshop "Physics of Exciton-Polaritons in Artificial Lattices" took place at the Center for Theoretical Physics of Complex Systems (PCS), Institute of Basic Science (IBS), in Daejeon, Republic of Korea, from the 15th to 19th of May, 2017. This workshop was coordinated by Dr. Timothy Liew (Nanyang Technological University, Singapore), Dr. Yuriy Rubo (UNAM, Mexico, and PCS IBS, Korea), and Dr. Ivan Savenko (PCS IBS, Korea). During those five days, there were 21 invited and 8 contributed talks on different aspects of exciton-polariton transport and condensation in semiconductor microcavities, spatially patterned and subject to artificial (engineered) periodic potential.

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

- Experiments on polariton condensation in the 1D and 2D Lieb lattices (and also in kagome and honeycomb lattices) as it follows from enthusiastic talks of Alberto Amo (C2N, CNRS, France), Sebastian Klembt (University of Würzburg, Germany), and Dmitry Krizhanovskii (University of Sheffield, UK). These experiments demonstrated the formation of compact polariton condensates loaded into the quasi-flat band formed in the Lieb lattice.
- Topologically protected states of exciton-polaritons have been addressed in the talks of Guillaume Malpuech (University of Clermont Auvergne and CNRS, France), Ivan Shelykh (University of Iceland, Iceland), Alexander Poddubny (ITMO University and Ioffe Institute, Russia), and Wijnand Broer (Nanyang Technological University, Singapore).
- Single-particle and quantum effects have been addressed in the talks of Daniele Sanvitto (NANO, CNR, Italy), Juan Camilo López (Autonomous University of Madrid, Spain), and Hugo Flayac (EPFL, Switzerland).
- Vortex formation and the Josephson oscillations have been highlighted in the talks of Mikhail Portnoi (University of Exeter, UK), Alberto Bramati (Pierre-and-Marie-Curie University, France), Alexey Yulin (ITMO University, Russia), Fabrice Laussy (University of Wolverhampton, UK), and Aleksandr Alodzhants (ITMO University, Russia).
- Finally, there have been very important talks on nonlinear polariton dynamics by Oleg Egorov (Friedrich Schiller University Jena, Germany), Vadim Kovalev (Institute of Semiconductor Physics, SB RAS, Russia), Nataliya Bobrovska (Institute of Physics, PAS, Poland) and Alexey Kavokin (University of Southampton, UK); on formation of coherence between two polariton condensates separated in the quantum wire by Luis Viña (Autonomous University of Madrid, Spain); two-dimensional theory of general coherence by Denis Karpov (ITMO University, Russia); formation of instabilities in exciton-polariton condensation by Michal Matuszewski (Institute of Physics, PAS, Poland); polariton networks by Tania Espinosa-Ortega (Nanyang Technological University, Singapore); engineering by proton implantation of structured potentials for exciton-polariton condensates by Michael Fraser (CEMS, RIKEN, Japan); and on spontaneous magnetization and magnetic ordering in polariton condensates by Hamid Ohadi (University of Cambridge, UK) and Helgi Sigurdsson (University of Iceland, Iceland).

The overall impression from the Workshop is that, while trying to mimic many effects in solid-state electronics and cold-atom systems, the exciton-polariton system possesses a number of unique and important ingredients, coming from the out-of-equilibrium nature, since polaritons represent driven-dissipative open system, and strong nonlinearity. These features permit to exploit and use the long-range coherence of the system for both fundamental studies and application-oriented research such as for networking and information control. The workshop demonstrated that semiconductor microcavities hosting exciton-polaritons is a realm of research which has strong potential to develop a new platform for optoelectronics and spin-optronics. Feedback from the different workshop participants was extremely positive. For those working on exciton-polariton physics, the PCS IBS is now seen as the place of choice for establishing new collaborations and the visibility of the local research done in this field has been further increased. Several researchers, particularly early-stage researchers, expressed a strong interest in working with PCS IBS in the future.

3.1.4 External Cofunding of Workshops and Seminars

- *Attosecond Physics at the Nanoscale*
  International Workshop: October 29 – November 2, 2018
  – 12% of the workshop budget contributed by the CASTECH (Center for Attosecond Science and Technology, Korea) within the MPK (Max Planck POSTECH/Korea Research Initiative)
- *Disordered Systems: From Localization to Thermalization and Topology*
  International Workshop: September 3 – 7, 2018
  – 30% of the workshop budget contributed by the APCTP (Asia Pacific Center for Theoretical Physics, Korea) and DIME (Daejeon International Marketing Enterprise, Korea)
- *Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems*
  International Workshop: September 18 – 22, 2017
  – 43% of the workshop budget contributed by the APCTP, DIME and ICTP (Abdus Salam International Centre for Theoretical Physics, Italy)

3.1.5 Advanced Study Group Reports

Spin-Active Electric Weak Links

Convener: Robert Shekhter

Our Advanced Study Group (ASG) was active throughout the calendar year 2018, during which its activities followed the approved research plan and timeline. Collaborative efforts during four meetings on-site at the PCS IBS 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. [1-8]). The three most significant scientific achievements, in our opinion, are the following:

- We have predicted that the spintro-mechanics of magnetic nanomechanical structures is strongly affected by single-electron Coulomb correlations. In particular, we have proposed that Coulomb promotion of a spin-induced nanomechanical shuttle instability is a viable method for single-electron manipulation of the nanomechanics of spin-active nanodevices [1].
- The possibility to generate an electronic spin-current mechanically is predicted for driven spin-orbit-active electric weak links [2, 3].
- Electric and magnetic gating effects on electron and spin transport through a spin-orbit-active nanowire were suggested as tools for detecting and measuring spin-orbit coupling in nanomaterials [4].

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

A. Pauli- and Coulomb constraints on the Rashba spin dynamics of two-electron tunneling

[5]. Work on this project started in 2017, during the time our ASG application for 2018 was being prepared. The first results were obtained in the autumn of 2017 and where published at the end of that year [6]. This work has been continued within the framework of our 2018 ASG. In this research we formulate a model for the transmission of pairs of electrons through a weak electric link in the form of a nanowire made of a material with strong electron spin-orbit interaction (SOI). In this model we emphasize the interplay between the effects of Coulomb interactions and the Pauli exclusion principle. The constraints, due to the Pauli principle, are shown to "quench" the coherent SOI-induced precession of spins when spatial wave packets of two electrons overlap significantly. This quenching, which results from projection of the pair's spin states onto spin-up and spin-down states in the link, breaks up the coherent propagation through the link into a sequence of coherent hopping that add incoherently. Applying the model to the transmission of Cooper pairs between two superconductors, we find that, in spite of Pauli quenching, the Josephson current oscillates with the strength of the SOI, and it may even to change sign (compared to the limit of the Coulomb blockade, when the quenching is absent).

B. Spin-polarized proximity states formed by Rashba-split electrons [7]. In this project we consider a new kind of superconducting proximity effect induced by the tunneling of "spin-split" Cooper pairs between two conventional superconductors connected by a normal conductor containing a quantum dot. The difference compared to the usual superconducting proximity effect is that the spin states of the tunneling Cooper pairs are split into singlet and triplet components by the electronic spin-orbit coupling, which is assumed to be active in the normal conductor only. We demonstrate that the supercurrent carried by the spin-split Cooper pairs can be manipulated both mechanically and electrically for strengths of the spin-orbit coupling that can be realistically achieved by the electrostatic gates.

C. Spin currents generated by the AC performance of spin-active electric weak links [2,3]. This research is motivated by a desire to harvest effects of the SOI on electron transport, which are absent in systems with time reversal symmetry. One way to break that symmetry is to consider devices with a time dependent spin-orbit coupling. An oscillatory spin-orbit interaction can be generated by a rotating electric field or, alternatively, by a nanomechanical rotation of the weak link. We have shown that new functionality of spin-orbit-active electronic weak links can be achieved by time-dependent mechanical deformation of the weak links. As an illustration, we use a simple model to calculate the electronic spin current generated by rotation of a bent spin-orbit-active nanowire coupled to the bulk metallic leads. We have also demonstrated that the electric weak link, subjected to the AC electric field, can function as a point-like generator of electron DC spin current.

D. Spin-promoted heat transport through a spin-active weak link [8]. During work on this project we have been focused on developing a theory of a thermally induced single-electron 'shuttling' instability in a magnetic nanomechanical device subjected to an external magnetic field. The model of the magnetic shuttle device, which was formulated, comprises a movable metallic grain suspended between two magnetic leads. The leads are kept at different temperatures and assumed to be fully spin-polarized with anti-parallel magnetizations. We have shown that, for a given temperature difference, mechanical shuttling occurs in a region of external magnetic fields between a lower and an upper critical fields which separate shuttling regime from a normal small-amplitude 'vibronic' regimes. We find that (i) the upper critical magnetic field saturates to a constant value in the high temperature limit and that the shuttle instability domain expands with a decrease of the temperature; (ii) the lower critical magnetic field depends not only on the temperature-independent phenomenological friction coefficient, used in the model, but also on intrinsic friction (which vanishes in the high-temperature limit). The feasibility of using thermally driven magnetic shuttle systems to harvest thermal breakdown phenomena is discussed as possible application.

E. Experimental activity. Experiments aimed at studying electrical conductance oscillations due to the electron spin-orbit coupling are planned based on ideas outlined in [4]. We expect that InGaAs nanowires have the necessary spin-orbit coupling strength, and devices are designed to satisfy the experimental requirements for measuring the nanowire conductance variation with respect to chemical potential and magnetic field. After resolving issues in providing transparent contacts between the nanowire and electric leads, the conductance oscillations predicted in [4] are expected to be observed at low temperatures.

In addition to work performed according to the ASG working program for 2018, a number of new projects have been initiated as the result of the ASG:

- Single-electronic manipulation of spintromechanics
- AC driven spintronics of Rashba-weak links
- Kondo tunneling through Rashba interferometer
- Numerical study of SOI active networks
- Electric and magnetic gating of SOI affected transport

We shall continue to work on them in accordance with the approved working program for our 2019 ASG.

In conclusion, we would like to mention that we are very satisfied with important progress on several fronts, which were not parts of our original research goals within the 2018 ASG program. To mention just a few we highlight the following:

- Strong synergy effects in the work of our international ASG team have been achieved. Our meetings at the PCS were important for the formulation of research plans, for completing projects, and for preparing manuscripts for publications.
- Several researchers from outside the ASG (both from Korea and the EU) have expressed willingness to collaborate with us within the ASG program. A list of associated members (in this sense) of the ASG is presented in the attachment.
- A significant part of the associated ASG members (see attachment) are young Korean and European scientists. We especially appreciate the young Korean experimentalist Chulki Kim, who joined us recently and will become an ASG member in 2019.
- Our experience from the ASG activities regarding the international collaboration, established within the ASG, has the potential to facilitate establishing new links between the PCS and other European centers of advanced research covered by support from the European Commission. One example is the recently signed Agreement for Scientific Cooperation between the PCS and the Center of Excellence “QuantixLie”, hosted at the Faculty of Science, University of Zagreb, Croatia.
- Our ASG activity has generated new directions for spin-related research programs.

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. Heeyun Lee and Ms. Gileun Lee, as well as all other staff and technical support members.

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List of members

- *Formal members:*
  Robert Shekhter (University of Gothenburg, Sweden)
  Amnon Aharony (Ben-Gurion University of the Negev & Tel Aviv University, Israel)
  Ora Entin-Wohlman (Ben-Gurion Univ. of the Negev & Tel Aviv University, Israel)
  Mats Jonson (University of Gothenburg, Sweden)
  Ilya Krive (B.Verkin Inst. for Low Temp. Physics and Engineering, NASU, Ukraine)
  Danko Radić (University of Zagreb, Croatia)
  Hee Chul Park (PCS IBS, Korea)
  Junho Suh (KRISS, Korea)

- *Associate members:*
  Sang-Jun Choi (PCS IBS, Korea)
  Loenid Gorelik (Chalmers University of Technology, Sweden)
  Olya Ilinskaya (B.Verkin Inst. for Low Temp. Physics and Engineering, NASU, Ukraine)
  Minjin Kim (KRISS, Korea)
  Jihwan Kim (KRISS, Korea)
  Mikhail Kiselev (ICTP, Italy)
  Nojoon Myoung (Chosun University, Korea)
  Chulki Kim (KIST, Korea)
  Kun Woo Kim (PCS IBS, Korea)
  Sejoong Kim (UST, Korea)

Edge Reconstruction in Quantum Hall Systems and Topological Insulators

Convener: Igor Yurkevich

This Advanced Study Group has focused on theoretical investigations of edge reconstruction in quantum Hall systems. The ASG activities included numerous discussions on development of advanced mathematical apparatus to attack various problems related to the edge physics which we briefly list below.

- Igor Yurkevich and Victor Kagalovsky addressed the problem of emergence of a superconducting edge state resulted from repulsive inter-mode interaction between Kramer's doublets (helical modes) existing at the edge of a quantum spin Hall system. The discussion was joined by Vladimir Yudson.

- Yuval Gefen, Igor Lerner and Igor Yurkevich finalized a co-authored paper on a detection protocol of Quantum Discord. This term refers to a measure which identifies quantumness of states, even if they are not entangled.
- Yuval Gefen had extensive discussions with Dmitry Polyakov (workshop participant) on the interplay between electric conductance and heat conductance on the edge of fractional quantum Hall systems, and how this results in quantum noise with certain peculiar properties.
- Yuval Gefen had extensive discussions with Udit Khanna on how to implement Heiblum's "engineered edge" to design parafermions (without the need to invoke superconductors).
- Yigal Meir and Yuval Gefen had constructive discussions on energy spectroscopy on the edge of an integer QH state, detecting various electron-electron inelastic scattering processes.
- Dimitry Gangardt had numerous discussions with the members of the institute: Sergej Flach, Ivan Savenko, and Alexei Andreanov, as well as the members of the ASG (Yuval Gefen and Victor Kagalovsky). The main topics discussed were the ongoing projects at the PCS, his own research on ultracold atom thematic and how they can fit together. Dimitry Gangardt also continued to work on his manuscript on full counting statistics of weakly interacting bosons.
- Moshe Goldstein with Yuval Gefen, Jinhong Park and Jukka Vayrynen (workshop participant) formulated a model for the reconstruction transition, and examined the role played by disorder, finding that in a wide parameter regime disorder will not localize the edge stripe created by reconstruction.
- Moshe Goldstein, Yuval Gefen and Udit Khanna developed a model aiming at developing a new platform for the creation of tunable integer and fractional helical edge state, have shown intriguing change in sign in the Landau fan slope, and examined the peculiar effect of exchange. Furthermore, together with Yigal Meir we have extended the method to the fractional case.

We believe that the discussion between the ASG members will result in papers published shortly after. We will continue our collaborations throughout the year.

Members:
Igor Yurkevich (Aston University, UK)
Dimitry Gangardt (University of Birmingham, UK)
Yuval Gefen (Weizmann Institute of Science, Israel)
Moshe Goldstein (Tel Aviv University, Israel)
Victor Kagalovsky (Shamoon College of Engineering, Israel)
Udit Khanna (Tel Aviv University, Israel)
Ki-Seok Kim (POSTECH, Korea)
Igor Lerner (University of Birmingham, UK)
Yigal Meir (Ben-Gurion University of the Negev, Israel)
Jinhong Park (Weizmann Institute of Science, Israel)
Vladimir Yudson (National Research University Higher School of Economics, Russia)

Topological Phases in Arrays of Luttinger Liquid Wires

Convener: Alexander Chudnovskiy

The Advanced Study Group focused on theoretical investigations of interaction effects on the helical edge state of topological insulators. In particular, we addressed the following issues:

- Can interactions modify the properties of edge states, leading to formation of charge-density wave or superconducting pairing instabilities?
- Can the combination of interactions and symmetry conserving scattering lead to localization of edge states?
- In the case of multiple edge states, how many of them can remain delocalized in presence of interactions and disorder scattering?

To address those questions properly, we had to develop a solid starting point for Luttinger liquid description that took into account specific properties of edge states of topological insulator (TI). We started from the model of one-dimensional chain that reproduces the dispersion of the edge state of topological insulator, and generalized that model to multiple chains with the aim to describe the edge carrying multiple Kramers doublets. This stage of our project was performed in the period from August 28 till August 30, 2017. The formulation of the chain model was lead by A. Chudnovskiy, in close cooperation with I. Yurkevich, V. Kagalovsky, and F. Kusmartsev.

On the next stage of our investigations, we introduced charge-density interactions in the chain model, and, performing the transition to the continuous description at large length scale and low energies, derived and classified the interactions between the helical modes of the edge states of topological insulators. In that way, we reached the proper formulation of the Luttinger liquid model for topological edges. This part of investigation required careful analysis of length and energy scales. It was performed in the period from August 31 till September 8, 2017. A. Chudnovskiy and F. Kusmartsev performed the calculational part of the work, all four members of ASG discussed and analyzed the obtained results.

Once formulated, the Luttinger liquid model was analyzed with respect to its stability against spatially homogeneous interactions, as well as against single- and multi-particle scattering by local potentials. To this end, we performed the diagonalization of the multichannel Luttinger liquid model at hand, using the methodology, which was developed by I. Yurkevich in his earlier works. After diagonalization of the model, explicit forms of the spatially homogeneous operators describing interactions in the charge-density fluctuations (charge channel) and between the superconducting pairing fluctuations (Josephson channel) were identified. Diagonalization of the multichannel Luttinger liquid model and derivation of explicit expressions for the operators of interactions was performed by I. Yurkevich. All members of the ASG participated in the discussion of results and performed independent check of calculations. This part of our activity took the time from September 9 till September 13, 2017.

Calculating the scaling dimensions of the operators of interactions, we determined their relevance or irrelevance in the renormalization group sense. The relevance of interactions in one of the channels signaled the instability of the multichannel Luttinger liquid leading to formation of charge density wave or superconducting ordering. In both cases, a gap opens in the spectrum of single particle excitations, and transport through the Luttinger liquid channels involved in the interaction becomes blocked. Calculation of scaling dimensions was performed by V. Kagalovsky, and checked independently by I. Yurkevich and A. Chudnovskiy.

Basing on the analysis of scaling dimensions, we constructed the phase diagram, describing the stability/instability of multichannel edge states against homogeneous interactions for different values of Luttinger liquid parameters. Construction of the phase diagram was lead by V. Kagalovsky in close collaboration with A. Chudnovskiy, I. Yurkevich, and F. Kusmartsev. F. Kusmartsev played the leading role in the classification of different instabilities and resulting phases that arise after break down of Luttinger liquid. This part of our activity was performed in the time from September 14 till September 19, 2017.

Finally, we calculated scaling dimensions of operators describing spatially local single- and multiparticle scattering processes. Our results show, that in presence of interactions only a single Luttinger liquid channel can be preserved from localization by scattering on disorder potential. This is in contrast to previous believe, that, for example in case of two Kramers doublets, both of them can be preserved from localization in presence of interactions. Calculation of scaling dimensions and construction of phase diagram was lead by V. Kagalovsky, and independently checked by A. Chudnovskiy and I. Yurkevich. All members of the ASG discussed the obtained results and worked out their physical interpretation. This final stage of our work took place from September 20 till September 24, 2017.

During the final stage of our work, we discussed future developments of our project, in particular, the sliding Luttinger liquid description of the array of semiconducting wires on a superconducting substrate, which forms the array of so-called Kitaev chains. In this discussion, we set benchmarks for future scientific cooperation.

The ASG members gave three talks in the PCS IBS seminar:

- “Metal-insulator transition in sliding Luttinger liquid” by V. Kagalovsky on September 5, 2017,
- “Exotic quantum phases and their control in spinor Bose condensates” by A. Chudnovskiy on September 7, 2017,
- “Superconducting pairing in 2-chain Luttinger liquid” by F. Kusmartsev on September 14, 2017.

We attended numerous talks at the two workshops that were held at the PCS during our stay:

- International Workshop “Flatband Networks in Condensed Matter and Photonics,”
- International Workshop “Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems.”

The ASG activities included numerous discussions with members of the PCS IBS, in particular with I. Savenko, H.C. Park, A. Andreanov, K. Viligas, M. Thudiyangal as well as with other visitors of the PCS IBS, in particular Y. Rubo and M. Fistul.

Finally, we are pleased to inform, that the paper “Metal-insulator transition in a sliding Luttinger liquid with line defects” by A.L. Chudnovskiy, V. Kagalovsky, and I.V. Yurkevich resulted from our collaboration in the ASG “Anderson Localization in Topological Insulators” held at the PCS IBS in 2016 was accepted for publication in the Physical Review B.

We believe that the current ASG activity will result in several publications. We will continue our collaboration through the year and obviously will be very happy to repeat our visit to Daejeon.

In conclusion, we would like to thank IBS PCS for a great scientific environment! Special thanks go to Dr. Dominika Konikowska, Ms. Sol Cho, and Ms. Heeyun Lee for perfect organization of our visit and all-round help during our stay at the PCS IBS.

Members:

Alexander Chudnovskiy (University of Hamburg, Germany)
Victor Kagalovsky (Shamoon College of Engineering, Israel)
Fedor Kusmartsev (Loughborough University, UK)
Igor Yurkevich (Aston University, UK)

Dissipative Quantum Chaos

Convener: Sergey Denisov

Our ASG runs for three months – February, August, and October, which constitute three stages of the group work. The activity of the ASG will be concluded with the workshop "Dissipative Quantum Chaos: from Semi-Groups to QED Experiments," held at the PCS IBS on October 23 – 27, 2017.

February. This was the initiation of the group work. We figured out two problems, discussed and started to work on them. The problems are summarized into two corresponding questions:

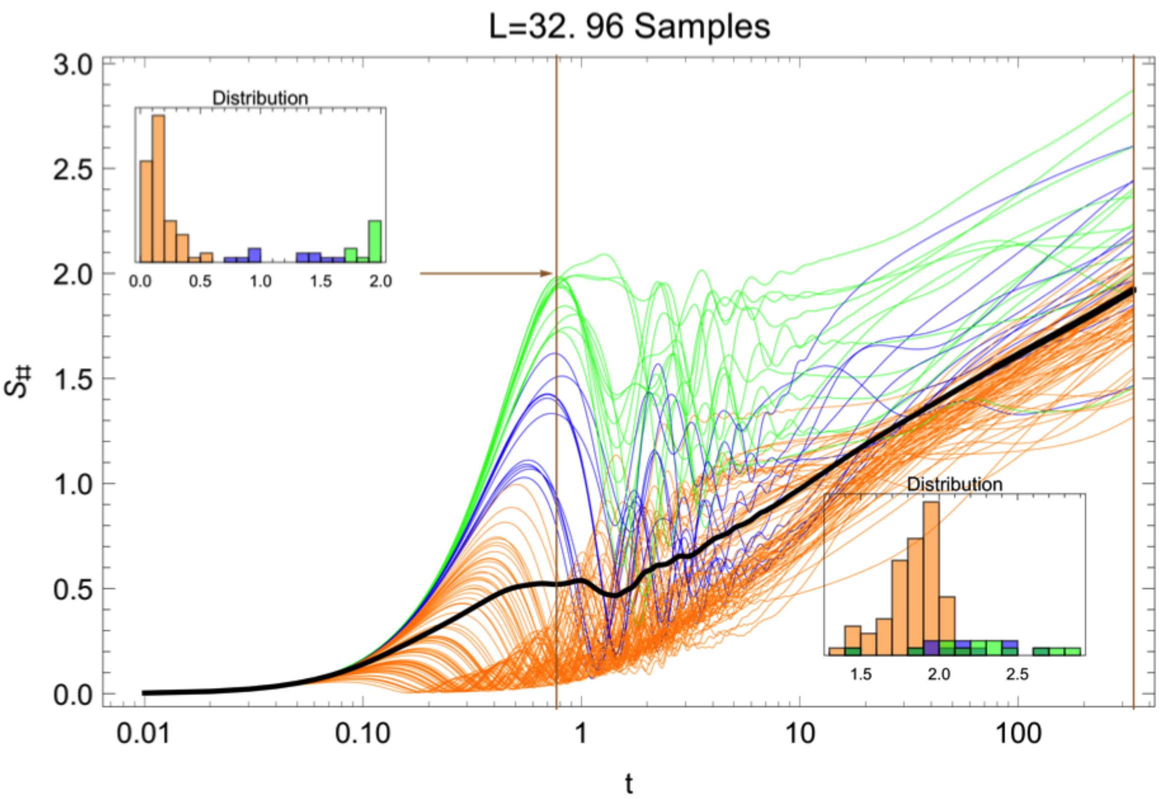
- Can we see footprints of many-body localization in the asymptotic state of an open quantum system?
- Are there Floquet Lindbladians?

The *first question* is of interest in many different context and for many reasons, ranging from pure theoretical to experimental ones. Assume we have a quantum system that exhibits many-body localization (MBL) phenomenon in the Hamiltonian limit [1]. Can we still see the MBL when the system is made open, i.e. it is subjected to dissipation? If it is possible then it would be a big deal: We will have (i) a unique state (not a set of eigenstates) which is, in addition, (ii) stable (with respect to perturbations), and (iii) will be able to control localization properties of this state. Very recent updates on the front of the MBL studies declared that the standard-like dephasing dissipation washes out the MBL, so that eventually an MBL system ends up in a maximally mixed state - independently of whether it was at the MBL phase or not in the Hamiltonian limit [2]. So, a specific non-trivial dissipation is the key prerequisite. This relates our studies to another 'hot' field, which is dissipative engineering of many-body states [3].

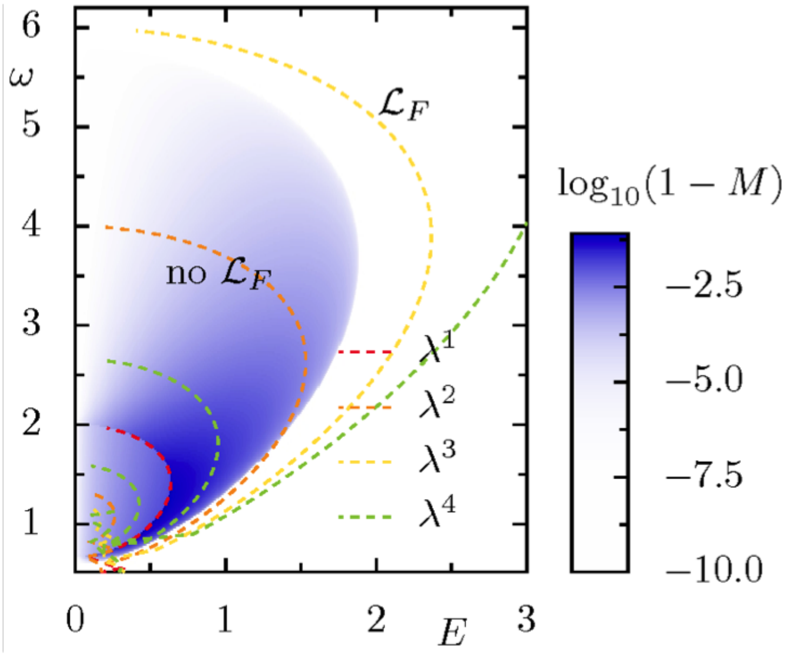
As for the members of the ASG, Mikahil Ivanchenko is involved (we will continue in August, when he comes with a Ph.D. student, Igor Yuspiov). There are also members of the PCS are involved, that are Sergej Flach (who has a large expertise on disorder-induced localization phenomena and natural interest to many-body localization) and Ph.D. student Ihor Vakulchyk (who has substantially advanced our numerical studies by bringing in the Matrix Product Operator (MPO) machinery [4] which allowed us to handle open quantum systems consisting up to 50 spins; see figure below).

The *second question* is very interesting *per se* because this is a case when physical intuition (well, at least of most of the experts we have consulted) fails. Imagine that you have a quantum system that is periodically driven (in other words, the corresponding Hamiltonian is a time-periodic Hermitian operator) and, in addition, open. The dynamics of such system can be described with the Lindblad equation having a time-periodic generator on the rhs. Would it be possible to construct time-independent Lindblad generator (which we called "Floquet Lindbladian") yielding at stroboscopic instants of time - T, 2T, 3T, ... - the same states of the system as in the case of original time-dependent generator? This is indeed possible when the system evolution is unitary, i.e., the dissipation is set to zero. Then the generator (now is in the rhs of the Schrödinger equation) is the Hermitian operator, the propagator over one period is its time-ordered exponent and, therefore, is a unitary operator. Thus, any branch of the logarithm of the latter could serve as a time-independent generator (also called "Floquet Hamiltonian" [5]). So the answer is always "yes" in the Hamiltonian limit.

It is not longer true when the system is open. This is because of the very specific structure of the Linblad equation [6]. In fact, as we demonstrate with a simple qubit model,



Floquet Lindbladian does not exist in the most interesting case when the driving is neither diabatic nor adiabatic. This direction is handled by a member of the ASG, André Eckardt, and his Ph.D. student, Alexander Schnell (who performed all numerical simulations and thus visualized the answer; see figure below). We plan to continue along this direction and finalize those studies in a paper in October.



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August. We finalized our paper on the signatures of many-body localization (MBL) in open quantum systems (see report for February for more information) [1].

Together with Dario Poletti and Michael Ivanchenko, we discussed the issue of time crystals in MBL systems, with the main focus on Floquet time crystals. The latter are systems that exhibit time-periodic oscillations (in term of some relevant observables) with a period being a multiple of the period of the driving (in most cases it is a period-doubling); in other words, such systems violate the discrete time translation symmetry imposed by the driving.

The key question was about introducing the dissipation in time-crystal systems in order to make them more 'stable' (hopefully) as clocks. We unfolded this question into the problem of time crystals in open systems, both classical (Markov continuous processes) and quantum ones. As it stands now (see recent works [2,3]), time crystals are only possible in the thermodynamic limit, when the number of the system parts (spins, bosons, sites) goes to infinity. In this case, the appearance of time crystals corresponds to period doubling bifurcations in the corresponding non-linear mean-field equations. We think that it is indeed true for the classical open systems. However, it is not so in the quantum case: it is possible to have a perfect time crystal in a finite-size quantum system. We will continue in this direction in October.

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October. Two members of the group, Mikhail Ivanchenko and Igor Yusipov, finished and submitted a paper on quantum Lyapunov exponents (it is published now as a Rapid Communication in PRB [1]). Three others, Sergey Denisov, André Eckardt, and Alexander Schnell, continued to work on their paper "Is there Floquet Lindbladian?" (see February's report; it is on arxiv now [2]). There was a lot of discussions on the issue of Floquet time crystals in open quantum systems, with the whole group participating in them. The outcome was rather inconclusive but at the end the issue did not look so promising as it seamed at the beginning.

We had a great event in October, directly related to the ASG work, that is the International Workshop "Dissipative Quantum Chaos: from Semi-Groups to QED Experiments," with a lot of relevant participants and talks.

Most important, there was a series of inspiring discussions with Karol Życzkowski, Dariusz Chruściński, Tomaž Prosen and Marko Žnidarič. Particularly, with Karol and Dariusz, we discussed a very interesting issue - "How to define and sample random Lindbladians?" These discussions (and initiated collaboration) resulted in a joint work [3]. I consider it as one of the most valuable outcomes of the group work in October.

[1] I.I. Yusipov, T.V. Laptyeva, and M.V. Ivanchenko, Phys. Rev. B 97, 020301(R) (2018).
[2] A. Schnell, A. Eckardt, S. Denisov, arXiv:1809.11121 [quant-ph].
[3] S. Denisov, T. Laptyeva, W. Tarnowski, D. Chruściński, K. Życzkowski, arXiv:1811.12282 [quant-ph].

Final report. In the retrospection, the work of the ASG is but a success. Most important, the agenda of the ASG "Dissipative Quantum Chaos" has been set (suffice it to say that group's participants – now themselves, without the ASG convener – organized in 2019 another workshop on the subject – 708. WE Heraeus-Seminar "Quantization of dissipative chaos: ideas and means" in Bad Honnef, Germany).

Many collaborations were initiated at the PCS IBS due to the ASG and the accompanying workshop. For example, it sparked the ongoing collaboration between K. Życzkowski, D. Chruściński, and S. Denisov (see a recent joint work [1]). The workshop has been noticed by the international community (the organizers got an invitation for a special issue in CHAOS from the editor-in-chief).

As for the scientific questions which were planned to address during the group activity, they were addressed thoroughly [1-5]. Even more, many other questions were discussed, new problems were formulated and new projects were launched. For example, a project on quasi-stationary states in open quantum systems, with participation of the PCS IBS researchers, was initiated [6].

As to formal quantifiers, the group work resulted (by now) in two published papers [2,3] (both are published as Rapid Communications in PRB) and three submitted papers [1,4,5] (with two of them passing through second refereeing rounds in PRL [1,4]).

[1] S. Denisov, T. Laptyeva, W. Tarnowski, D. Chruściński, K. Życzkowski, arXiv:1811.12282 [quant-ph].
[2] I.I. Yusipov, T.V. Laptyeva, and M.V. Ivanchenko, Phys. Rev. B 97, 020301(R) (2018).
[3] I. Vakulchyk, I. Yusipov, M. Ivanchenko, S. Flach, and S. Denisov, Phys. Rev. B 98, 020202(R) (2018).
[4] A. Schnell, A. Eckardt, and S. Denisov, arXiv:1809.11121 [quant-ph].
[5] S. Denisov, T. Laptyeva, W. Tarnowski, D. Chruściński, K. Życzkowski, arXiv:1811.12282 [quant-ph].
[6] I. Vakulchyk, M. Ivanchenko, S. Flach, and S. Denisov, *Quasi-stationary states in open quantum systems*, http://adsabs.harvard.edu/abs/2018APS..MARK26011V

3.1.6 Lectures, Colloquia, Symposia and Seminars at the Center

Date	**Title**	**Speaker**
13.12.2018	Sparse modeling approach to many-body problems	H. Shinaoka, Japan
11.12.2018	Geometrical frustration	A. Samanta, India
04.12.2018	Exactly solvable two-dimensional lattice models with boundaries	P. Pearce, Australia
03.12.2018	When a Symmetry Breaks	H. Murayama, USA

27.11.2018	Dynamics of topological excitations in single- and multi-component Bose-Einstein condensates	K. Kasamatsu, Japan
23.11.2018	The past, present and future of the gravitational wave science	H.M. Lee, Korea
22.11.2018	Thermoelectric transport through a quantum dot system: crossover between non-Fermi liquid and Fermi liquid behavior	T.T.K. Nguyen, Vietnam
20.11.2018	Two-stage Kondo effect	M. Kiselev, Italy
06.11.2018	Exploring non-equilibrium phases of matter using controlled quantum systems	M.-J. Hwang, Germany
25.10.2018	Multi-dimensional synthetic photonics lattices	A. Sukhorukov, Australia
23.10.2018	Two-body localised state in interacting quantum walks	L. Toikka, Austria
19.10.2018	Electromagnetics applications using cylindrical structured beams	I. Rondón, Mexico
16.10.2018	Reconstruction of the polarization distribution and topological physics in one-dimensional systems	M. Yahyavi, Turkey
11.10.2018	HgTe based topological insulators	D. Kvon, Russia
10.10.2018	Explaining slow relaxation in jammed materials and aging in terms of record fluctuations	S. Boettcher, USA
04.10.2018	Thermoelectricity in tunneling nanostructures	S. Kruchinin, Ukraine
27.09.2018	Signatures of replica symmetry breaking in SYK model	A. Chudnovskiy, Germany
21.09.2018	Response to defects in multi- and bipartite entanglement of isotropic quantum spin networks	S. Singha Roy, Korea
20.09.2018	The repulsive Bose-Hubbard model at negative temperatures: problems and prospects	A. Cherny, Russia
18.09.2018	Nonlinear dynamics of discrete mechanical systems with flat dispersion bands	N. Perchikov, Israel
13.09.2018	Fresh insights fromzero-temperature non equilibrium dynamics of spin glasses	A. Sharma, India
11.09.2018	Time-dependent quantum transport in nano junctions with time-varying components	E. Cuansing, Philippines
10.09.2018	Disorder-dressed evolution in edge-mode transport and beyond	C. Gneiting, Japan
04.09.2018	Investigating topological structures by microwave experiments with coupled dielectric resonators	U. Kuhl, France

28.08.2018	Many-body localization and thermalization in isolated quantum systems	R. Mondaini, China
23.08.2018	Classification of flat bands form irremovable discontinuities of Bloch wave functions	J.W. Rhim, Korea
22.08.2018	The unexplored world of composite quantum particles: two effects taken from cold-atom physics	S.-Y. Shiau, Singapore
21.08.2018	Suppression of thermal nano mechanical oscillations by heat flow	L. Gorelik, Sweden
09.08.2018	Anisotropic magnetic interactions in transition metal oxides: the cases for Sr2RuO4 and Sr2VO4	B. Kim, Korea
31.07.2018	Strong Field Physics Explored with a multi-PW laser at CoReLS	C.H. Nam, Korea
26.07.2018	Effective formalism for open-quantum-system dynamics: Time-coarse-graining approach	C.-W. Lee, Korea
20.07.2018	Supersymmetric photonics for engineering applications	S. Yu, Korea
12.07.2018	Chiral pair of Fermi arcs, anomaly cancellation, and spin or valley Hall effects in Weyl metals with broken inversion symmetry	K.-S. Kim, Korea
11.07.2018	Quantum criticality in Kitaev-Ising mode	J.-H. Han, Korea
06.07.2018	Topological Defects and Phase Transitions	J.M. Kosterlitz, USA
04.07.2018	Noise on complex edges: ballistic channels and heat diffusion	J. Park, Israel
03.07.2018	Stability of a topological insulator: interactions, disorder and parity of Kramers doublets	V. Kagalovsky, Israel
19.06.2018	Excite-state quantum phase transition and quantum speed limit time	Q. Wang, China
14.06.2018	Probing the String Landscape Implications, Applications, and Altercations	K.R. Dienes, USA
12.06.2018	Cavity QED effects in low dimensional systems	K.B. Arnardóttir, Singapore
07.06.2018	Excitation of localized states in the flat band of exciton-polariton Lieb lattice	M. Sun, Korea
31.05.2018	Photon drag effect in hybrid systems	I. Savenko, Korea
24.05.2018	Machine that learns and searches for new particle and laws in physics	S. Nam, Korea
23.05.2018	2-dimensional quantum gas in non-equilibrium	H. Yang, Korea
17.05.2018	Quantum many-body physics of superconducting qubits arrays	K. Shulga, Japan

15.05.2018	Some studies on modifications of low dimensional systems under the application of periodic driving	T. Mishra, India
10.05.2018	Classical simulator for quantum two-level system and its application in a nanoelectromechanical device	A. Parafilo, Italy
09.05.2018	Disordered Floquet topological insulators	K.W. Kim, Korea
02.05.2018	Quantum phase diagram of the S=1 bilinear-biquadratic model on the star lattice	H. Lee, Japan
24.04.2018	Plasmonics: From materials to artificial colors and metasurfaces	O. Martin, Switzerland
17.04.2018	Nonlinear phenomena in one-dimensional granular metamaterials	K. Vorotnikov, France
12.04.2018	Doublon-holon origin of the sub peaks at the Hubbard band edges	S.-S. Lee, Germany
04.04.2018	Electromechanics of the pore in vesicle fusion: Self-organized super sensitivity to electrical stimulus	K.-H. Ahn, Korea
03.04.2018	Dynamics of embedded topological solitons in the Josephson junction array	Y. Zolotaryuk, Ukraine
29.03.2018	Analytic calculation of the conformal partition functions of critical bond percolation on the square lattice	P. Pearce, Australia
28.03.2018	Localization and transport in kicked rotor and its variants	S. Paul, India
27.03.2018	Instanton approach to optical bistability	C.-W. Lee, Korea
22.03.2018	Spin-assisted heat transport in nano mechanical shuttle structure	R. Shekhter, Sweden
20.03.2018	Far-field probing of topological states in all-dielectric metasurfaces	D. Smirnova, Russia
15.03.2018	Resonant Bragg structures	V. Chaldyshev, Russia
14.03.2018	Spin orbit interactions, time reversal symmetry and spin filtering	A. Aharony, Israel
13.03.2018	Spin transport and dynamics in non-uniform magnetic structures	K.-J. Kim, Korea
12.03.2018	Using supersymmetry to study condensed matter systems	P. Padmanabhan, Korea
13.02.2018	Theoretical description of hybrid polaritonic nanostructures	D. Karpov, Austria
07.02.2018	Topologically-protected transport in ring resonator lattices	D. Leykam, Korea

31.01.2018	Multi-orbital correlations and spin-orbit couplings in ruthenate	H.J. Lee, Korea
30.01.2018	Exotic elastic properties of layered two-dimensional materials	S. Woo, Korea
18.01.2018	Derivation of a Markov model that violates detailed balance	J. Lee, Korea
16.01.2018	Dynamics of a charged Brownian particle in the low mass limit	J.D. Noh, Korea
15.01.2018	Figure of merit of quantum dot-based spintronical thermoelectric	I. Krive, Ukraine
12.01.2018	Spin-orbit-coupled multiorbital Hubbard models: J-freezing, Hund's rules, and excitonic magnetism	A. Kim, UK
10.01.2018	Correspondence principle of work distribution in Bose-Hubbard model	Q. Wang, China
20.12.2017	Topological Photonics and Topological Insulator Lasers	M. Segev, Israel
20.12.2017	Scaling theory for unipolar resistance switching	B. Kahng, Korea
20.12.2017	Dynamical tuning of pairing cutoff: Pairing mechanism of the FeSe-monolayer and related systems	Y. Bang, Korea
20.12.2017	Many-body localization of a quantum computer	B. Altshuler, USA
12.12.2017	Photo electron cutoff in dense media	J.-M. Rost, Germany
12.12.2017	Fold, staple, and mutilate: kirigami for 2D electronic materials	D. Campbell, USA
12.12.2017	Nonreciprocal responses in solids	N. Nagaosa, Japan
12.12.2017	Coupled transport in chains of nonlinear oscillators	A. Politi, UK
08.12.2017	Identification materials by combination of first principle calculations with experiment	I. Fongkaew, Thailand
07.12.2017	Quartic anharmonicity and negative thermal expansion of ScF	S. Jungthawan, Thailand
06.12.2017	Experiments with superconducting microwave resonators emulating artificial graphene	B. Dietz, China
04.12.2017	High-frequency electron transport in a miniband superlattice under phonon driving	A. Apostolakis, UK
29.11.2017	Thermoelectric transport through SU(N) Kondo impurity	M. Kiselev, Italy

23.11.2017	Exploring the Universe via Gravitational waves in the era of multi-messenger astronomy	C. Kim, Korea
16.11.2017	Dissipative generation of non equilibrium quantum steady states with reduced rank	V. Popkov, Germany
15.11.2017	Hybrid percolation transitions: criticality and explosion	B. Kahng, Korea
14.11.2017	Classical and quantum X waves orbital angular momentum	M. Ornigotti, Germany
30.10.2017	Biophysical modeling for glucose homeostasis: environment-dependent synchronization of active rotators	T. Song, Korea
24.10.2017	Non-equilibrium spin systems – from quantum soft-matter to nuclear magnetic resonance	I. Lesanovsky, UK
20.10.2017	Noise-enhanced quantum control	J. Goetz, Finland
19.10.2017	Dimensional study and ionic molecule device on ultra-thin manganite film	B. Kim, Korea
18.10.2017	The spintronics of adsorbates	N. Lorente, Spain
13.10.2017	Decoherence due to gravity: Open quantum system approaches	J. Han, Korea
12.10.2017	Korean fusion energy development program and role of the KSTAR	H.K. Park, Korea
26.09.2017	Some aspects of superfluidity in the one-dimensional Bose gas	A. Cherny, Russia
14.09.2017	Superconducting pairing in 2-chain Luttinger liquid	F. Kusmartsev, UK
07.09.2017	Exotic quantum phases and their control in spinor Bose condensates	A. Chudnovskiy, Germany
05.09.2017	Metal-insulator transition in sliding Luttinger liquid	V. Kagalovsky, Israel
05.09.2017	Magnetic order control through an optical vortex radiation	Y. Goto, Japan
05.09.2017	Excitation processes by nano-structured light fields	N. Yokoshi, Japan
29.08.2017	Topological Photonics	A. Szameit, Germany
23.08.2017	Interplay of dissipation and interaction in quantum many body systems: perfect spin diode and instability transitions	D. Poletti, Singapore
22.08.2017	Control of localization in open systems	I. Yusipov, Russia
17.08.2017	Chaotic behavior of disordered nonlinear systems	H. Skokos, South Africa

01.08.2017	Damping of two-level system Rabi oscillation due to interaction with excitonic bath	V. Kovalev, Russia
28.07.2017	Observation of anapole with dielectric nanoparticles	A. Miroshnichenko, Australia
13.07.2017	Chiral anomaly in disordered Weyl semimetals	J. Lee, USA
30.06.2017	Electronic properties in correlated materials: State-of-the-art calculations exploiting quantum information	K. Halberg, Argentina
13.06.2017	Quantum Coulomb Glass: Anderson localization in an interacting system	H.-J. Lee, Korea
01.06.2017	Mattereality in collaboration of Art and Science	Y. Kim, Korea
31.05.2017	Topological Dirac insulator	Y. Kim, Korea
24.05.2017	Mixed-pairing superconductivity in 5d Mott insulators with antisymmetric exchange	A. Akbari, Korea
24.05.2017	Wave functions for large electron numbers	P. Fulde, Germany
27.04.2017	Analogue gravity by an optical vortex. Resonance enhancement of Hawking radiation	V. Fleurov, Israel
26.04.2017	Tunable periodicity of Josephson junction by non-Abelian exchange statistics of Majorana zero modes	S.-J. Choi, Korea
25.04.2017	On systems with and without excess energy in environment - ICD and other interatomic mechanisms	L. Cederbaum, Germany
18.04.2017	Dualities in multichannel Luttinger liquids	I. Yurkevich, UK
18.04.2017	Bulk-boundary correspondence from the intercellular Zak phase	J.W. Rhim, Germany
17.04.2017	Geometric phase at graphene edges - scattering phase shift of Dirac fermions	S-J. Choi, Korea
13.04.2017	Efficient impurity solver for large cluster-extension dynamical mean field theory calculations	H. Lee, Korea
11.04.2017	Wannier-Stark states, Bloch oscillations and related transport problems for a quantum particle in tilted lattices	A. Kolovsky, Russia
06.04.2017	For whom the Belle tolls	Y. Kwon, Korea
04.04.2017	Macroscopic quantum superpositions in thermalizing and many-body localized systems	C.-Y. Park, Korea
23.03.2017	First-principles approach to correlated systems: LDA and beyond LDA	C.H. Kim, Korea
21.03.2017	Mechanically controlled electronic spin in electric weak links	R. Shekhter, Sweden

16.03.2017	Applications of Metamaterials: Cloaking, Photonics, and Energy Harvesting	K. Kim, Korea
07.03.2017	Towards the extreme events predictability	A. Maluckov, Serbia
02.03.2017	One-dimensional S=1 quantum spin systems under frustration and anisotropy	H.J. Lee, Korea
16.02.2017	Non-equilibrium condensation of weakly interacting bosons in the presence of thermal baths: temperature-dependent dissipation	A. Schnell, Germany
07.02.2017	A percolation approach to two-particle localization in the Bose-Hubbard model	T. Engl, New Zealand
06.02.2017	Search for Muon to Electron Conversion at J-PARC – the COMET Experiment	Y. Kuno, Japan
24.01.2017	Radiation-induced coherent quantum phenomena in the ballistic transport of graphene based n-p and n-p-n junctions	M. Fistul, Korea
18.01.2017	The hunt for double-beta decay and nEXO	G. Gratta, USA
11.01.2017	Dynamical confinement-deconfinement transitions in many-body localized topological phases	B. Kang, USA
10.01.2017	Synthetic field-induced charge density waves	D. Radić, Croatia
05.01.2017	When spin liquids order... but just a bit	L. Jaubert, Japan

3.1.7 Long-term Visitor Reports

Condensation of nonequilibrium bosons in artificial potentials

Yuriy Rubo: April 3, 2017 – April 1, 2018

The exciton-polaritons (or shortly polaritons) are quasiparticles representing mixed states of photons confined in a semiconductor microcavity and excitons in quantum wells embedded inside the microcavity. They are localized either in one (for the plane microcavities) or in two or three (wires and dots) spatial directions, and their properties inherit from both the light and matter. In particular, due to the photon component they possess very small effective mass (about 10^{-4} of the free electron mass) and they interact strongly with each other due to the exciton component. These properties allow efficient polariton relaxation and condensation up to room temperatures. Contrary to the atomic condensates, the system of polaritons is driven-dissipative and essentially nonequilibrium. The polaritons are created in the microcavity by external pumping and they escape because of the finite transparency of Bragg mirrors that compose the microcavity. When the harvest rate of particles into a particular state becomes higher that the leakage rate from it, i.e., above the threshold, the state is occupied by big number of polaritons: condensation occurs. The condensation is accompanied by emission of coherent light from the microcavity, even when excitation comes from an incoherent source, and this is referred to as polariton lasing. The main advances in the theory of nonequilibrium condensation and lasing of polaritons in periodic potentials are presented below.

The first line of research consisted in the study of nontrivial and technologically important problem of the polariton condensation in one-dimensional wire with periodic potential and position-dependent losses, i.e., subject to some complex periodic potential. In particular, we have been working on the polariton condensation in the ring excitation geometry, for the case when the condensate is formed in quasi one-dimensional narrow ring with periodic potential. We assume that the period of potential a is much smaller than the size of the ring, and that condensation take place at the edges of the first Brillouin zone. We have shown that the static condensate is unstable and there happens spontaneous generation of superfluid polariton currents. Spontaneous breaking of rotational symmetry of a polariton condensate emerges at a critical pumping, and the superfluid current direction is stochastically chosen. For large rings, a peculiar spatial current domain structure emerges, where the current direction is switched at the domain walls. As a result, for a polariton condensate in the ring geometry there is no stationary condensate state without the flux, and this flux is not quantized [1].

To get additional insight into the dynamics of out-of-equilibrium polariton condensation, we consider a 1D polariton system with complex periodic potential and nonlinearities due to polariton interactions and gain saturation. We note that for the detailed description of the nearly flat-band exciton-polariton condensation it is necessary to account for the imaginary part of periodic potential, which describes the distributed losses in the microcavity, and also allows for different gain of single-particle states due to the phonon-assisted relaxation. By carefully choosing the parameters (height and width) of the potential, we find that the condensate state can be transformed from 0-state to π-state (or vice versa) with increasing interactions (or decreasing dispersion of the miniband). The resulting state of the condensate is counter-intuitive, as it does not correspond to the state with minimal losses. The crossover from 0 to π-condensate happens by formation of propagating dark solitons. This is demonstrated by studying the solutions of 1D Gross-Pitaevskii equation ($\hbar = 1$)

$$i\partial_t\psi = -\frac{1}{2m^*}\partial_x^2\psi + V(x)\psi + (g - i\beta)|\psi|^2\psi, \tag{1}$$

where ψ is the wave function of polariton condensate, $V(x) \equiv V(x + a)$ is the complex periodic potential, $V(x) = V_{\mathrm{re}}(x)+iV_{\mathrm{im}}(x)$, g is the polariton-polariton interaction constant, and β describes the gain-saturation nonlinearity of the system. We note that both real and imaginary parts of potential can be tuned by modulation of the profile and the strength of external pumping.

We investigated the condensation into single band, i.e., when only one band has positive imaginary part of the energy. Four different cases can be present even in this simple case. They can be labeled as AA, AV, VA, and VV, according the sign of the effective mass of the minibad at $k = 0$ and the position of maximum gain. The first letter V(A) correspond to the positive (negative) effective mass, respectively, while the second letter V(A) indicate that the positive imaginary part of the energy is minimized (maximized) at $k = 0$, respectively. If the interactions are negligible, $g \ll \beta$, then one expects to obtain the condensation of bosons in the state with maximal gain, that is the formation of zero condensate for the AA and VA cases, and the formation of π-condensate in the AV and VV cases. The positive gain for these condensates is stabilized by the gain saturation nonlinearity, and this is indeed what is observed by the numerical simulation of (1) starting from a random seed. Inclusion of finite polariton-polariton repulsion does not change this result for the VA zero-condensate and for the AV π-condensate. They remain stable solutions even for $g \gg \beta$. On the other hand, the condensates for the AA and VV cases demonstrate reconstruction of the wave function in the short range. Consider, for example, the AA case. Initially, the noninteracting polaritons are condensed in the $k = 0$ state, which corresponds to the maximal gain. With increasing interaction constant there appear the fragments of π-condensates. Since they correspond to the finite wave vector, either $+\pi/a$ or $-\pi/a$, the π-condensate droplets behave as solitons, moving either to the right or to the left, respectively. When interaction nonlinearity becomes even more stronger, the size of droplets increases, they proliferate, creating the spatial-temporal intermittency in the system. Finally, at large interaction, a uniform π-condensate is formed. It should be noted that the formation of π-condensate in this system is not related to the energy minimization or gain maximization, as it is accompanied by the decrease of the condensate occupation. See Ref. [2] for more details about reconstruction and intermittency phenomena.

The second research line consisted in elaboration of the theory of polarization states of networks of trapped polariton condensates. This theory was aimed to address experimental observations by Jeremy Baumberg's group from the University of Cambridge, UK. The state of a single trapped condensate is characterized by polarization bifurcation into one of two nearly circularly polarized states, so that each condensate behaves as an effective Ising spin. The behavior of networks of these spins, however, is highly nontrivial. For the case of chains of condensates, we have demonstrated that multiply coupled spinor polariton condensates can be optically tuned through a sequence of spin-ordered phases by changing the coupling strength between nearest neighbors. At strong Josephson coupling between the condensates all condensate are formed with the same handedness of the polarization (ferromagnetic alignment). With increasing of the potential barriers between the condensates (and thus decreasing of the Josephson coupling) the chain of condensates undergoes the transition into new, paired configuration, where each spin has one neighbor with the same spin and the other neighbor with the opposite spin: $\ldots\uparrow\uparrow\downarrow\downarrow\uparrow\uparrow\downarrow\downarrow\ldots$. Subsequent decrease of the Josephson coupling leads to formation of antiferromagnetic order: $\ldots\uparrow\downarrow\uparrow\downarrow\uparrow\ldots$. And only at very weak Josephson coupling (strong barriers between the condensates) the polarization states become essentially random. The presence of new paired phase, and the fact that all these spin phases take place at the same sign of the Josephson coupling, distinguish these nonequilibrium exciton-polariton networks from the usual magnetically ordered spin systems. By modeling the system of trapped polariton condensates with coupled driven-dissipative Gross-Pitaevskii equations, we have shown theoretically that the phase transitions can be explained from minimization of the bifurcation threshold which determines the magnetic order as a function of the coupling strength. This allows the control of multiple magnetic orders via adiabatic (slow ramping of) pumping [3, 4]. We have also investigated the stability of spin polarized states of single trapped condensate and the Kramers transitions between the states with opposite handedness (spin flips) produced by the noise [5].

Creating *quantum correlations and entanglement* in the polariton condensate networks has been subject of the third research direction. We demonstrated the potential of quantum operation using lattices of polaritons in patterned semiconductor microcavities. By introducing an inverse four-wave mixing scheme acting on localized modes, we have shown that it is possible to develop non-classical correlations between individual condensates. This allows a concept of quantum exciton-polariton networks, characterized by the appearance of multimode entanglement even in the presence of realistic levels of dissipation. Entanglement between two polariton condensate is demonstrated in the framework of effective Hamiltonian

$$\hat{H}_{\text{eff}} = \frac{\alpha}{2}(\hat{a}_1^2 + \hat{a}_2^2 + \hat{a}_1^{\dagger 2} + \hat{a}_2^{\dagger 2}) - J(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1), \tag{2}$$

where $\hat{a}_n^\dagger$ $(\hat{a}_n)$ are the creation (annihilation) operators of nth polariton condensate $(n = 1, 2)$ and J is the Josephson coupling constant. Here each condensate is created by two lasing beams with amplitudes $a_{L(U)}$ due to the four-wave mixing scattering process, described with $\alpha_0(\hat{a}_n^{\dagger 2} a_L a_U + \text{h.c.})$, by setting $\alpha = \alpha^* = \alpha_0 a_L a_U$ (complex values of α can be accounted for by the gauge transformation). The entanglement of two condensates can be evidenced by the Peres-Horodecki criterium extended for continuous variables: $S_{12} = (1/2)[\mathcal{V}(\hat{q}_1 - \hat{q}_2) + \mathcal{V}(\hat{p}_1 + \hat{p}_2)] \leq 1$, where $\hat{q}_n = (\hat{a}_n + \hat{a}_n^\dagger)/\sqrt{2}$, $\hat{p}_n = (\hat{a}_n - \hat{a}_n^\dagger)/i\sqrt{2}$, and the operator variance $\mathcal{V}(\hat{O}) = \langle \hat{O}^2 \rangle - \langle \hat{O} \rangle^2$. As a result, for $J > \alpha$ we obtain $S_{12} = (J + \alpha \cos(2\omega t))/(J + \alpha)$, where $\omega = \sqrt{J^2 - \alpha^2}$. This indeed demonstrates entanglement of the condensate states for negative values of the cosine function.

We concluded that the evolution of polariton networks from the classical to quantum regime implies finding a mechanism of generating quantum correlations that can overcome the dissipation of the system. Nonlinearity, in the form of polariton-polariton interactions is traditionally weak, however, we have shown theoretically that an inverse four-wave mixing scheme allows enhancement to an effective strongly nonlinear regime. Local nonlinearity and standard Josephson coupling between spatially separated modes is then sufficient to generate quantum entanglement both between pairs of modes and multiple modes [6].

Last but not least research activity was dedicated to the study of *temporal evolution of polariton wave packets* in 2D polariton lattices with flat bands and in the presence of spin-orbital coupling. In the former case, using an example of a realistic two-dimensional exciton-polariton Lieb lattice with distributed losses, we have shown [7] that the (nearly) flat band in this system possesses a small but finite dispersion, both in the energy and the lifetime of the states. We have demonstrated the possibility to excite compact localized condensates in this nearly flat band using resonant Laguerre-Gaussian pulses. In spite of the small dispersion of the band, the localization and coherence of compact localized condensates remain well defined. They exhibit an unusual dynamics, manifested by modulated fast Rabi oscillations. The coherent compact localized condensates can be maintained for times much longer than the polariton lifetime in the presence of an incoherent homogeneous background pumping. The coherent excitation of compact polariton condensates opens different possibilities to use the polariton Lieb lattice as a platform for network computations. In particular, it permits one to construct graphs of compact localized condensates and exploit them for classical optical simulations. Both the phase and polarization of localized condensates can be used to encode information.

The polarization dynamics and motion of polariton wave packets becomes rather spectacular in the presence of spin-orbital coupling. The wave packet propagation is not straight, but trembling around the classical trajectory – the phenomenon known as *zitterbewegung*. We have theoretically studied the zitterbewegung of exciton-polaritons in the driven-dissipative system of a 2D microcavity characterized by the longitudinal-transverse (LT) polarization splitting of polariton modes. We have shown [8] that the condensed polaritons propagate in the cavity plane following an oscillating trajectory that appears as a result of the pseudospin rotation in the course of the motion of the polariton wave packet. This prediction opens the way to a direct observation of the counterintuitive zitterbewegung trajectories in an optical experiment. Such an observation would have a significant fundamental importance as evidence of an effect predicted in the early days of quantum mechanics. The planar semiconductor microcavities with a tailored LT splitting of eigenmodes may serve us a convenient laboratory for studies of nontrivial trajectories of quantum wave packets. The polariton polarization degree is strongly affected by the zitterbewegung, which helps experimental observation of the effect. We have found the optimized control parameters of the system that would help observation of the zitterbewegung on the length scale of tens of micrometers.

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[7] Meng Sun, I.G. Savenko, S. Flach, and Y.G. Rubo, Phys. Rev. B 98, 161204(R) (2018).

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Coherent quantum dynamics in strongly correlated superconducting quantum metamaterials

Mikhail Fistul: January 15 – December 14, 2017

During the period of January 15 – December 14, 2017, Dr. Mikhail Fistul participated in the following activities:

Magnetically induced transparency of a metamaterial composed of twin qubits. This work has been carried out in the collaboration with Dr. K. Shulga (Russia & Japan); Dr. E. Ilichev, Prof. A. Ustinov (Germany); Prof. O. Astafiev (UK).

Quantum metamaterials, media built from quantum objects acting as meta-atoms, promise to display novel light-matter interaction phenomena. Nonclassical electrodynamics of such media is linked to many-body quantum mechanics of quantum simulators, ensemble quantum memory, generation of non-classical light states, etc. In this work we demonstrate intriguing electrodynamic properties of a superconducting quantum metamaterial fabricated from an array of meta-atoms, each consisting of a pair of superconducting loops coupled via a tunnel junction (twin flux qubit). Such meta-atoms provide a strong coupling between qubits and propagating electromagnetic waves. The peculiarity of the twin qubit structure is the field induced 0 to π transition of the Josephson junction phases that leads to an abrupt suppression of the microwave transmission in a broad frequency range. In a narrow frequency range, we observe a great enhancement of the microwave transmission. Such resonant transparency is controlled by an external magnetic field. The detailed quantitative analysis is in a good accord with measurements. The results were published in [1].

NbN based superconducting Josephson phase qubit with AlN tunnel barrier: evidence for Purcell effect. This work has been carried out in collaboration with Dr. M. Lisitskiy (Italy) and Prof. A. Ustinov (Germany).

The theoretical analysis of the relaxation time of the superconducting qubit under non-equilibrium conditions was presented. In proposed model the main source of qubit relaxation is the interaction with weakly dissipative resonant two-levels systems. We obtain that the relaxation time of qubit is strongly determined by the population of excited states. The population of exciting states can be greatly enhanced by applying the resonant microwave pulses. In this non-equilibrium state the relaxation time is increased by one order of magnitude. This effect resembles a well known Purcell effect for the relaxation time of qubit strongly interacting with the cavity. Our theoretical analysis is in a good accord with experiments carried out on NbN/AlN/NbN phase qubit in the presence of resonant microwave pulses.

This work was presented at the ISEC 2017 conference (June 12 – 16, 2017, Sorrento, Italy) and was published in [2].

Localization phenomenon in the one-dimensional discrete time quantum walk: localization length, dispersion and different types of disorder. This work has been carried out in collaboration with Prof. S. Flach, Dr. P. Qin and Ph.D. student I. Vakulchyk (PCS IBS).

A theoretical study of the phenomenon of Anderson localization in a generalized discrete time quantum walk will be reported. The generalized discrete time quantum walk is controlled by a quantum coin unitary matrix on each step of particle motion. The quantum coin matrix depends on four angles that can be engineered with microwave pulses in qubit chains. In the absence of disorder in quantum coins parameters the quantum walk dynamics is determined by two-bands dispersion relationship which becomes completely flat in the limit of vanishing kinetic energy. Various types of disorder result in the localization of quantum particle. In particular, kinetic energy disorder leads to logarithmic divergence of the localization length at spectral symmetry points. By making use of the transfer matrix technique we were able to obtain analytical expressions for the frequency dependent localization length in two limits, i.e. weak and strong disorder, and we anticipate that it will be useful for various applications.

The work has been published in [3,4] and it was presented at 4th International Conference on Quantum Technology (ICQT 2017, August 12 – 16, 2017, Moscow, Russia).

Photon-induced valley Hall effect in 2D Dirac semiconductors. This project has been done in collaboration with Prof. I. Savenko (PCS IBS); Prof. V. Kovalev (Novosibirsk, Russia); W.-K. Tse (Alabama, USA).

We present a theoretical analysis of Hall valley conductivity in 2D Dirac semiconductors subject to a large power high frequency electromagnetic field (EF). We obtain that under such conditions the valley Hall transport is determined by EF induced intensive resonant interbands transition, and therefore, the dynamics of photon-dressed quasiparticles (PDQs). The PDQs are characterized by specific quasienergy spectrum, displaying the dynamical gap that strongly depends on on the amplitude and polarization of applied EF, and the non-equilibrium distribution function are determined by the ratio of intraband scattering and interband recombination times. We use our analysis in order to calculate the nonlinear optically induced Hall valley effect in the two-dimensional transition-metal dichalcogenides (e.g. $MoS2$), and a strong enhancement of Hall conductivity is obtained as the photon energy of EF is close to the energy gap between conduction and valence bands of 2D semiconductor.

The work has been published in [5].

Microwave properties of high-kinetic inductance resonator based on disordered superconducting films: Josephson junction network model, effective self- and cross-Kerr nonlinearities. This work has been carried out in the collaboration with Dr. I. Pop, Dr. N. Maleeva (Germany); Prof. A. Karpov (Russia).

The motivation for this theoretical study is the experimental observation of a power dependent shift (enhancement) of the resonant frequency of superconducting disordered films. We have elaborated a particular model of a disordered thin superconducting films that is suitable for an analysis of microwave properties, resonances, nonlinearities etc., in such systems. In this model the superconducting film is presented as the network of strongly coupled Josephson junctions. The dynamics of such network is characterized by time- and coordinate dependent Josephson phases. By making use of the Kirchhoff laws and the well-known RSJ model for a single Josephson junction we obtain the dynamic equation describing the microwave properties of high-kinetic inductance resonator in the presence of an external drive. The excitation of cavity modes in such a system results in a set of cavity resonances characterized by a weak dispersion. Moreover, as an intensity of externally applied microwave radiation increases the Kerr-type of nonlinearity starts to play important role. We obtain a substantial shift of resonant frequency. Another effect is the cross-Kerr nonlinear coupling between two modes and of the resonator. Our theoretical predictions are in a good accord with experimental measurements of superconducting stripline resonators fabricated from disordered $Al/AlOx$ films.

The work has been published in [6].

Coherent collective quantum phenomena in disordered arrays of interacting superconducting qubits. As a part of this project the invited talk: "Coherent collective quantum oscillations in disordered arrays of interacting superconducting qubits" has been presented at the International Workshop "Dissipative Quantum Chaos: from Semi-Groups to QED Experiments" (October 23 – 27, 2017, PCS IBS). The pdf file of the presentation is available at the PCS IBS internet site.

A theoretical study of coherent collective quantum response in various disordered arrays of interacting superconducting qubits was presented. As a particular model an array of superconducting qubits embedded in the transmission line was addressed. I discuss both different types interaction between qubits, i.e. the inductive nearest-neighbors interaction and long-range interaction induced by exchange of virtual photons, and various on- and off-diagonal types of disorder. I show that the resonances in the frequency dependent transmission coefficient, $D(\omega)$, are directly determined by the time-dependent quantum-mechanical correlation function $C_i(t)$ of qubits. These collective excitations can be mapped to the Anderson localization of spinon-type excitations.

As the next step the coherent quantum oscillations of disordered arrays of superconducting qubits in the presence of long-range dissipative interaction (the global interaction) can be studied. We focus on the transmon or charge types (a weakly non-linear oscillator) of qubits, where collective effects occur due to equalizing the winding numbers of different qubits.

Giant persistent photoconductivity in monolayer MoS_2 *field effect transistors.* This work has been carried out in the collaboration with the group of Prof. A. Turchanin (Germany). This work is relevant to the research team "Light-Matter Interaction in Nanostructures" established at the PCS IBS.

Long-living photoconductivity induced by ultraviolet irradiation is experimentally recently observed in monolayer MoS2 field effect transistors. This giant persistent photoconductivity (GPPC) effect was found to be remaining at room temperature for an extremely long time period with a decay time constant of the order of 80 days. Furthermore, a huge enhancement of photo-induced, gate voltage dependent conductivity of the order of 10^6 was observed at room (RT) and low (LT) temperatures. We propose the quantitative analysis of this phenomenon by making use of the following model: the applied UV irradiation induces inter-bands transitions in monolayer MoS_2 and forms a large number of electron-hole pairs which quickly separates in space due to spatial variations of the band structure. Under such conditions, the recombination time of photo-carriers drastically increases causing the GPPC effect. Comparison of theoretical analysis with experimental observations allowed the extraction of important parameters of the model, such as the characteristic fluctuations of the band structure, the correlation radius of the random potential, the dependence of concentration of photoelectrons on the intensity of UV irradiation, and its decay time constant.

This work was presented on the DPG–Frühjahrstagung (March 11 – 16, 2018, Berlin Germany).

Resonant frequencies and spatial correlations in frustrated arrays of Josephson type nonlin-

ear oscillators. This work has been carried out in the collaboration with Prof. A. Andreanov (PCS IBS).

A theoretical study of resonant frequencies and spatial correlations of Josephson phases in frustrated arrays of Josephson junctions is presented. Two types of one-dimensional arrays, namely, the diamond and sawtooth chains, are discussed in detail. For these arrays in the linear regime the Josephson phase dynamics is characterized by multiband dispersion relation $\omega(k)$, and the lowest band becomes completely flat at a critical value of frustration, $f = f_c$. In a strongly nonlinear regime such critical value of frustration determines the crossover from non-frustrated ($0 < f < f_c$) to frustrated ($f_c < f < 1$) regimes. The crossover is characterized by the thermodynamic spatial correlation functions of phases on vertices, φ_i, i.e. $C_p(i-j) =< cos[p(\varphi_i-\varphi_j)] >$, displaying the transition from long- to short-range spatial correlations. We found that higher-order correlations functions, e.g. $p = 2$ and $p = 3$, restore the long-range behavior deeply in the frustrated regime, $f \simeq 1$. Monte-Carlo simulations of the thermodynamics of frustrated arrays of Josephson junctions are in good agreement with analytical results. We also outline the extension of our results to the case of kagome lattice, prototypical 2D frustrated lattice, and other higher dimensional lattices.

This work will be published in [7] and it was presented at the International Workshop "Flatband Networks in Condensed Matter and Photonics" (August 28 – September 1, 2017, PCS IBS), and the 2nd PCS Internal Workshop (Retreat, November 8 – 10, 2017).

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[2] M.P. Lisitskiy, J. Lisenfeld, M.V. Fistul and A.V. Ustinov, *NbN based superconducting Josephson phase qubit with AlN tunnel barrier*, IEEE Xplore proceedings (ISEC 2017).

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3.2 Appointments and Awards

Since the foundation of the PCS, several research fellows moved to faculty positions. *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.

The *University of Science and Technology (UST)* appointed the following PCS researchers as faculty members: *Alexei Andreanov, Mikhail Fistul, Sergej Flach, Daniel Leykam, Hee-Chul Park, Jung-Wan Ryu, Ivan Savenko.*

3.3 Teaching and Education

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, Mikhail Fistul, Sergej Flach, Daniel Leykam, Hee-Chul Park, Jung-Wan Ryu, 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.

3.4 Equipment and Premises

3.4.1 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 64 nodes, 2 CPUs per node, 12 & 14 cores per CPU, i.e. a total of 1664 cores, and 64 GB memory per node. For specific tasks, such as long time integrations of coupled ordinary differential equations with limited RAM need, we offer a GPU cluster with about 15,000 GPU cores. Furthermore, we have installed several 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 zero clients (terminals) 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. The IT department is currently managed by two employees.

3.4.2 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 450 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. All related information can be found on the library webpage (http://ctpcs.ibs.re.kr/Library.php) by way of the PCS homepage, where users are able to register.

3.5 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 Scientific Advisory Board meeting took place in December 2016, whereas the next meeting is scheduled for April 2019.

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	Seoul National University, Korea
Dai-Sik Kim	Seoul National University, 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

3.6 Members of the Center

(as of Dec. 31, 2018)

Position	**No.**
Director	1
Research Fellow	21
– Junior Research Team Leader	4
– Deputy Team Leader	1
– Visiting Research Fellow	2
Researcher	2
Ph.D. Student	7
Administrative staff	4
– Visitor Program	2

P.: Position
D: Director
T: Tenure-track
YSF: IBS Young Scientist Fellow
RF: Research Fellow
R: Researcher / Ph.D. Student

Name	**Period**	**Country**	**P.**	**Research team**
Ilias Amanatidis	09/16 - 12/17	Greece	RF	Quantum Many-Body Interactions and Transport
Alexei Andreanov	since 09/15	Russia	RF	Complex Condensed Matter Systems
Hwa Sung Cheon	03/15 - 03/17	Korea	RF	IT Manager
Sang-June Choi	since 11/17	Korea	RF	Quantum Many-Body Interactions and Transport
Carlo Danieli	since 11/16	Italy	RF	Complex Condensed Matter Systems
Mikhail Fistul	since 01/17	Russia	RF	Complex Condensed Matter Systems
Sergej Flach	since 12/14	Germany	D	Complex Condensed Matter Systems
Ara Go	since 11/16	Korea	T	Strongly Correlated Electronic Systems
Jungyun Han	since 03/18	Korea	R	Theoretical Photonics
Kicheon Kang	since 07/18	Korea	RF	Quantum Many-Body Interactions and Transport
Yagmur Kati	since 04/16	Turkey	R	Complex Condensed Matter Systems
Kun Woo Kim	since 07/18	Korea	RF	Quantum Many-Body Interactions and Transport
Dogyun Ko	since 03/18	Korea	R	Light-Matter Interaction in Nanostructures
Dominika Konikowska	since 04/16	Poland	RF	Visitor Program Coordinator
Hyeong Jun Lee	since 03/18	Korea	RF	Strongly Correlated Electronic Systems
Jaehyoung Lee	since 02/17	Korea	R	IT Manager
Minyoung Lee	since 06/16	Korea	R	IT Staff
Daniel Leykam	since 08/17	Australia	YSF	Theoretical Photonics
Wulayimu Maimaiti	since 10/15	China	R	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport

Merab Malishava	since 09/17	Georgia	R	Complex Condensed Matter Systems
Nojoon Myoung	04/16 - 08/17	Korea	RF	Quantum Many-Body Interactions and Transport
Pramod Padmanabhan	since 04/18	India	RF	Theoretical Photonics
Anton Parafilo	since 09/18	Ukraine	RF	Quantum Many-Body Interactions and Transport
Hee Chul Park	since 05/15	Korea	T	Quantum Many-Body Interactions and Transport
Pinquan Qin	05/15 - 05/18	China	RF	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Ajith Ramachandran	05/16 - 04/18	India	RF	Complex Condensed Matter Systems
Irving Rondón	since 10/18	Venezuela	RF	Theoretical Photonics
Yuriy Rubo	04/17 - 04/18	Mexico	RF	Light-Matter Interaction in Nanostructures
Jung-Wan Ryu	since 10/15	Korea	RF	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Ivan Savenko	since 02/16	Russia	T	Light-Matter Interaction in Nanostructures
Meng Sun	since 02/16	China	R	Light-Matter Interaction in Nanostructures
Diana Thongjaomayum	since 04/17	India	RF	Complex Condensed Matter Systems & Strongly Correlated Electronic Systems
Mithun Thudiyangal	since 11/16	India	RF	Complex Condensed Matter Systems
Lauri Toikka	08/17 - 04/18	Finland	RF	Light-Matter Interaction in Nanostructures
Ihor Vakulchyk	since 10/16	Ukraine	R	Complex Condensed Matter Systems
Kristian Villegas	since 05/17	Philippines	RF	Complex Condensed Matter Systems & Light-Matter Interaction in Nanostructures
Sungjong Woo	since 04/18	Korea	RF	Quantum Many-Body Interactions and Transport

Sukjin Yoon	since 10/16	Korea	RF	Light-Matter Interaction in Nanostructures

Chapter 4

Publications

2018

Bum-Kyu Kim, Sang-Jun Choi, Jae Cheol Shin, Minsoo Kim, Ye-Hwan Ahn, H.-S. Sim, Ju-Jun Kim and Myung-Ho Bae, *The interplay between Zeeman splitting and spin-orbit coupling in InAs nanowires*, Nanoscale 10, 23175 (2018).

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