2015 – 2016

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

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 infrastructure setup, the first research fellows joined PCS in May 2015. The center is temporarily hosted on the Munji Campus of KAIST, and is expected to move into its new premises on the IBS Campus (currently under construction) by the end of 2017. The founding director *Prof. 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 an active and large Visitors Program. The Center's mission is to both contribute significantly and essentially to, and to promote the international research field of theoretical physics of complex systems. Additionally, the center concept includes an active and large Visitors Program. Its activities include the organization of Advanced Study Groups with a duration from one to three months, and focused international workshop, both related to rapidly developing topics in the area of the physics of complex systems. The Visitors Program and its activities will offer young scientists - both from the center and universities - a fast track contact pathway to 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 *Prof. Doochul Kim*, president of IBS, during the Inaugural Symposium on July 24 2015. *Dr. Hee Chul Park* joined 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 first Advanced Study Group *Many Body Localization and Non-Ergodicity*, and hosted two workshops.

Jan. 2016 - Oct. 2016: Dr. Ivan Savenko started to lead the activities of the Junior Research Team *Light-Matter Interaction in Nanostructures*. 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 hosted at PCS. One of our first research fellows - *Prof. Gentaro Watanabe* - accepted a faculty position at Zhejiang University in China.

Outlook: Dr. Ara Go will join and lead a new research team *Strongly Correlated Electronic Systems*. The center currently counts 23 members including PhD students, and three junior research teams.

The concept of the center will be successful only if it is accepted by the scientific community. For this reason the center undertakes strong efforts to ensure transparency and openness. The *Scientific Advisory Board* is an important board to promote these efforts.

1.2 Research Areas and Structure of the Center

At 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 *Prof. Sergej Flach*. Its research activities span a broad spectrum of topics: and are represented by the focus of several closely collaborating research teams:

- Research team *Complex Condensed Matter Systems* led by *Prof. Sergej Flach* and *Dr. 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 *Dr. 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 *Dr. Ivan Savenko*: semiconductor microcavities, exciton polaritons, quantum transport, open quantum systems, quantum coherence, dissipative solitons, quantum dots, spin in mesostructures, polariton devices (signal routers, THz sources and detectors, lasers).

1.3 Visitors and Workshop Program

Its envisaged large and active visitors program makes PCS a very unique research center within the Institute for Basic Science. The visitors program administers individual fellowships and scholarships for scientists at the center but also international workshops and advanced study groups.

The fellowships and scholarships are open to scientists at all levels of their career, from PhD students all the way to sabbatical support for professors. The duration of scholarships varies between few weeks to few years. Both scholarship and workshop applications are evaluated by separate selection committees that include external experts.

During the year 2016, 95 scientists visited the center, some as part of special programs. The center hosts several *Advanced Study Groups* per year to foster the exchange between outstanding 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 the Physics of Complex Systems.

1.4 Diversity

PCS Visitors Program's structure and flexibility allow us to support stays ranging from brief (a few days), through short- (up to a month), to long-term (several months or years), thus suiting schedules of literally any potential visitor. Moreover, we offer schemes for very different purposes of the 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 logistical support can be fully customised, thus we can accommodate practically any individual needs of our visitors. As a result, we have hosted by now scientists from 32 countries, benefitting at our Center from the rich diversity.

1.5 Research Networking

In accordance with its 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 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 Visitors Program's efforts in organizing workshops, ASGs, and individual visits, resulting in numerous occasions for scientific interactions.

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).

Institutional networking is currently mainly realized through joint international workshops. In 2015, PCS and APCTP organized a workshop *Nanomechanical systems: from new materials to new application*. In 2017 PCS and APCTP will run the *International Workshop on Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems*. In 2016, PCS actively participated in the running of NetSci 2016 (*International School and Conference on Network Science*) in Seoul. We also support the *Mesoscopic Society*, a subsection of the *Korean Physical Society* in its educational efforts and organize together an international workshop on *Quantum Electron Transport in Emerging 2D Materials*.

Internationally, numerous scientific collaborations connect PCS with many distinguished institutions worldwide, including École Polytechnique (France), University of Cambridge (UK), RAL STFC (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).

1.6 Division Complex Condensed Matter Systems
Head: 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 astonishing research progress on all levels, from basic and fundamental research to applications. This is due to the field's ability to cross-fertilize various research directions, both from its own broad spectrum such as many-body interactions, nonequilibrium transport, topological insulators, flat bands, spin glasses, and graphene, but most importantly also from other fields, such as statistical physics, the physics of matter-light interactions, quantum optics and photonics, to name a few. The above sets the frame for our thrive through advancing in the understanding of a variety of complex condensed matter systems, and defines the pathway of the activities of the Complex Condensed Matter Systems Division.

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 single particle localization in real space due to disorder, and in 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.

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 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 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 study how structural and bond disorder lead to an ordered state, different from that selected by thermal fluctuations. We are further exploring how constraints stemming from geometrical frustration affect the properties of a spin-glass. We are studying the classical Ising antiferromagnet on the pyrochlore lattice (spin-ice) with bond disorder, that exhibits a transition to a spin-glass phase. We are aiming at understanding how geometrical frustration modifies the critical properties of the transition from paramagnetic to spin-glass phase. We are also studying spin fragmentation in 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 the frustration induced long-range correlations.

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

Perspectives

The division and team were constituted January 2015 with the arrival of the Sergej Flach, but in reality scientific activities started with the hiring of the first team members in May 2015. One team member - Gentaro Watanabe - already arrived and left for a faculty position with Zhejiang University, China. Two junior research team leaders - Hee Chul Park and Ivan Savenko - joined us in 2015 and 2016 and are setting up their team activities in the fields of Quantum Many-Body Interactions and Transport, and Light-Matter Interaction in Nanostructures. A third junior research team is expected to start its activities before the end of 2016 in the broad field of Computational Condensed Matter Physics, with a focus on Strongly Correlated Electronic Systems.

Cooperations

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, KAIST Daejeon, Kyungpook National University, NIMS Daejeon).

International cooperations include geometric frustration (OIST Japan and STFC UK), sphere packing (Santa Fe Institute USA), non-Hermitian physics (Athens University and Patras University Greece, Columbia University USA, UNAM Mexico), flat bands (Technion Haifa and Tel Aviv University Israel, Nanyang Technological University Singapore, Tbilissi University Georgia, Belgrade University Serbia), and many-body dynamics (Augsburg University Germany, Trento University Italy).

A separate but strong cooperation during the transition period of the director is with Massey University New Zealand, in a variety of the above topics.

1.6.2 Quantum Many-Body Interactions and Transport
Team Leader: Hee Chul Park

The Quantum Many-Body Interactions and Transport (QM-BIT) team is one of three teams at the IBS Center for Theoretical Physics of Complex Systems (PCS). We are interested in all aspects of condensed matter physics such as quantum many-body interactions, disordered systems, mesoscopic electron transport, nonlinear dynamics, nano-electromechanical systems, and more.

Research Topics of the Quantum Many-Body Interactions and Transport Team

Topology in matter - Our team has studied a number of topics based on condensed matter physics, with plans to continue and extend to more fundamental concepts. One such topic, to better understand the properties of exotic materials, concerns electron transport in topological insulators with spatially correlated magnetic or non-magnetic disordered surfaces. We are intensively studying electron transport and topological properties of exotic materials with topological distortion, external potential, and magnetic or non-magnetic disorders. Exotic materials are coupled with the external environment by emergent fields resulting from a topological gauge field, and properties are revealed through system symmetries such as time-reversal symmetry, inversion symmetry, chiral symmetry, and so on. Notably, these materials must have gapless Dirac states on the boundary between different topologies: this argument promises metallic states on the surface of the topological insulators, which show quantum phase transitions by external perturbations. This topic is a current focus of both theoretical and experimental physicists, with some typical examples of 2D materials, quantum Hall systems, topological insulators, and so on.

It is known that every metal has a different workfunction on each facet. Topological insulator with broken time-reversal symmetry is governed by modified Maxwell equations due to the magneto-topological effect. An electric field induced by the large difference in workfunctions generates a magnetic field and a magnetic moment on the edge of the topological insulator. The electric field is coupled with the magnetic field, mediated by the spatial deviation of an axionic field which is of topological order. Electrons moving on the surface of the topological insulator experience the different potentials on each facet because every surface has a different workfunction. The workfunction manipulates axion dynamics through magnetic ordering on the edge of the topological insulator. Additionally, when electrons cross over another surface, many are scattered due to the spin-momentum locking effect.

Strain - Strain on graphene creates a high pseudo-magnetic field due to the gauge potential acting on pseudo spin. Now, consider the Haldane model of topological materials with second hopping and a locally finite magnetic dipole; if there are periodic super-lattices induced by strain on graphene, then graphene might show topological properties like the Haldane model from the hexagonal-like magnetic field. This system realizes the quantum Hall effect without a real magnetic field or topological properties.

Nano-electromechanical systems - Recently, the attention of both theoretical and experimental physicists has been concentrated on quantum nano-mechanical systems. With improvements in fabrication skill have come demands for new technology. The quick changes in technology require the development of extremely sensitive sensors to measure low power signals, while the origins of the limitations of present sensors demand to be discovered and themselves studied for useful aspects. The interplay between electromechanical and quantum effects - seen in the sensitivity to external stimuli such as electromagnetic fields and environmental conditions - is useful in the study of the quantum-mechanical motion of macroscopic systems, e.g. mechanical cantilevers, using electron transport and optical measurement of position. Quantum measurement related to nano-electromechanical systems (NEMS), which combine an electronic system with mechanical degrees of freedom, is a significant topic in condensed matter physics. These systems show a variety of nonlinear phenomena such as self-excited oscillation, spontaneous symmetry breaking, and others that our center has researched and published about.

In a nano-mechanical system, control parameters treated by constant values vary with respect to time when we are controlling the system. Since a nano-mechanical system has relatively smaller dissipation than a macroscopic system, studying the dynamics of a nano-electromechanical shuttle by changing the time-dependent parameters may give us strange dynamics and intuition about dissipation. The concept of controllable dissipation is quite attractive to scientists for the potential to efficiently control nano-systems with high Q factors. The mechanical properties of materials are strongly correlated with their electronic structures in case of layered materials, such as strain engineering transport and vibron-assisted transport. A possible area of interest is to investigate vibron-assisted electron transport using only the electric properties of a suspended graphene sheet, because the mechanical motion is treated by the gauge potential on electrons.

Dynamic Localization - Here, we want to provide an answer for the robustness of dynamic localization against the short range interaction between two particles. We consider two bosons interacting via a delta-function potential that are driven by a periodic kicking potential. The wave function for the two delta-function interacting bosons is computed, and a repulsive-interaction is considered that does not lead to the appearance of a bound state. Within this chosen basis, the matrix elements of the time evolution operator show different decay rates along the center of mass (super-exponential) and the relative momentum (algebraic) directions. Due to this qualitative difference in the decay properties of the matrix elements, dynamic localization is destroyed for the relative momentum, while being preserved for the center-of-mass momentum.

In addition to the topics reported above, we are interested in more fundamental quantum effects such as quantum resonance, quantum chaos, dynamic localization, quasi-periodicity and disorder, chirality of dynamic states, bulk-boundary correspondence of topological systems, and many-body interactions. 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 continue. All of our topics will be interconnected and realized through specific experimental systems by the manpower of our team and collaborators. Since we are convinced that all new scientific foundations emerge by the interplay between the realization of concepts and basic principles, we expect that the results of our research will not only answer fundamental questions but lead to even more fundamental questions.

Perspectives

Our research team was formed in May 2015 with Dr. Pinquan Qin and team leader Dr. Hee Chul Park, now with five collaborating members at present. Wulayimu Maimaiti, a student under the PCS Director, started to work with us as our first intra-center collaborator, followed by two more members, Dr. Nojoon Myoung and Dr. Ilias Amananditis, who joined in May and September 2016, respectively. Dr. Qin has studied fundamental quantum physics and quantum many-body interactions based on quantum kicked rotors. Dr. Myoung is interested in graphene devices and the topological properties of graphene by means of mesoscopic aspects. Dr. Amanditis calculates electron transport on topological insulators using Green's function method. Our collaboration topic is flat band generators conducted by W. Maimati. The focus of our team is to study the overall theory behind varied topics in fundamental condensed matter physics, such as topological properties, many-body interaction, and quantum phase transitions through electron transport and field theoretical descriptions.

Cooperation

We have numerous collaborators outside of our center at various universities and institutes worldwide. For theoretical studies, we are working with:

- KIAS (Young Woo Son - graphene/2D materials, Sungjong Woo - cold atom/2D materials, and Kun Woo Kim - TI thin film)
- Postech (Kiseok Kim - TI with magnetic disorder)
- APCTP (Jaeyoon Cho - bulk-boundary correspondence)
- Gothenburg University (Robert Shekhter - nano-electromechanical shuttle)
- Ioannina University (Elefterios Lodorikis - graphene optics)
- Donghua University (Binhe Wu - topological insulator with disorder)

We conduct experimental collaborations with:

- KIST (Chulki Kim -nanomechanics, strained graphene)
- KRISS (Suyong Jung - Graphene VHJ, Seung-Bo Shim and Junho Suh - nanomechanics)
- Yonsei University (Jaehoon Kim - TI, meta-materials, and mesoscopic systems)
- ETRI (Young-Jun Yu - gas sensors)
- UNIST (Minkyung Jung - graphene transport)

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

Currently, the team consists of three members: the junior research team leader, *Dr. Ivan Savenko, a Research Fellow, Dr. Sukjin Yoon, and a PhD student, Mr. Meng Sun.* With Mr. Sun we have started a new project: exciton polaritons loaded in staggered one-dimensional potentials. In particular, we are considering exciton-photon coupling in semiconductor microcavities in which separate periodic potentials have been embedded for excitons and photons. We show that this system supports degenerate ground-states appearing at non-zero in-plane momenta. Considering both equilibrium and non-equilibrium models, with explicit treatment of polariton-acoustic phonon scattering, we predict the condensation of polaritons into a spontaneously chosen momentum state. This is confirmed by calculation of the cross second-order correlation function and the sampling of stochastic trajectories. Two mode squeezing between different momentum states is also shown to give rise to non-classical correlations between condensates.

We have prepared the manuscript which is now submitted to Physical Review. This manuscript is the result of the project, where the main author is the PhD student, M.Sun.

The collaboration *network* includes Prof. T. Liew (Nanyang Technological University, Singapore) and Dr. H. Flayac (EPFL, Switzerland).

Beside scientific work, we have participated in three topical *conferences* (QD2016, Jeju, Korea, May 2016; PLMCN17, Nara, Japan, March 2016; and Statphys26, Leon, France, July 2016) and three *workshops* (mini-workshop "General aspects of exciton-polariton physics", The Australian National University, Canberra, Australia, May 2016; "Topological states of light and beyond", IBS, Daejeon, June 2016; and FNM2016, Tbilisi, Georgia, September 2016).

Dr. Yoon joined our group very recently (in the middle-October 2016). We have just started to discuss possible joint projects.

Future prospects

From the general prospective, we plan to *find and hire more people* in the group (PhD students and postdocs). Beside scientific work, we plan to participate in several conferences (in particular, PLMCN 18 in 2017 in Wuerzburg, Germany). Moreover, we are currently organizing a workshop "International Workshop on Physics of Exciton-Polaritons and Optics of Nanostructures" to be at IBS in May 2017.

The *scientific plans* include:

- We plan to develop a two-dimensional advanced Gross-Pitaevskii equation (GPE) approach accounting for the quantum noise and scattering of polaritons on acoustic phonons of the crystal lattice and investigate how different scattering mechanisms allow to precisely control loading of particles in topological periodic structures with account of all possible interaction mechanisms and dissipation channels (in two-dimensional systems). The collaboration includes Prof. T.C.H. Liew (Nanyang Technological University, Singapore) and Dr. H. Flayac (EPFL, Switzerland).

- Periodic potentials for exciton polaritons have been used to study the formation of gap solitons and Dirac cones. They are predicted to be prime candidates for the generation of topological polariton states, and hold high promise for implementation of quantum simulators. Controlled loading of polaritons into a particular energy state of a band-gap structure enforced by tight-trapping periodic potential remains a critical problem since experimentally observed behavior cannot be captured by theoretical description in a thermal equilibrium. We will consider staggered (spatially separated) periodic potentials and a non-equilibrium model to include stochastic treatment of fluctuations in the quantum driven-dissipative exciton-polariton system in such potentials with account of spin.

- We will consider exciton-polariton energy relaxation in surface acoustic wave (SAW) potentials (one-dimensional). In particular, we will use our nonequilibrium model to see the condensation of particles locked in such potentials and observe the transition from staggered to casual polariton formation with the SAW propagating along the sample. The main effect of the SAW is to grab and drag excitons of polaritons along the structure.

- We will consider quantum Jarzynskii and Crooks fluctuation relations in a one-dimensional exciton-polariton system trapped in a lateral quantum well under diabatic ramping. This project involves collaboration with Prof. Gentaro Watanabe (China).

- We have also started to study bosonic paramagnetic resonance in exciton-polariton systems (V.M.Kovalev, M.M. Glazov, Russia).

Cooperation

Strong collaboration inside Korea includes nitride-based whispery-gallery mode microcavities and pumping of arsenide-base microcavities (KAIST Daejeon). International cooperations include general quantum coherence in exciton-polariton systems (EPFL, Lausanne, Switzerland), polariton-based devices (Wuerzburg, Germany), exciton polaritons in artificial lattices (NTU, Singapore; ANU, Canberra, Australia), exciton-polariton transport and dissipative solitons (ITMO University, Saint-Petersburg, Russia), hybrid Bose-Fermi systems (NSTU, Novosibirsk, Russia), quantum-mechanical work and fluctuation relations (Hangzhou, China).

Chapter 2

Selection of Research Results

Contents

2.1 Quasiperiodic driving of Anderson localized waves in one dimension

C. Danieli, S. Flach

The phenomenon of Anderson localization in disordered lattices [1] is highly susceptible to alterations of the phase coherence of the wave dynamics. A loss of phase coherence may lead to complete delocalization [2, 3]. In Ref. [4] we study the impact of a multi-color (*quasiperiodic*) driving of diagonal disorder in a one-dimensional chain with incommensurate frequencies. One of the driving questions was to understand how many colors D it needs to essentially recover an incoherent wave dynamics from a formally coherent quasiperiodic one, by studying the localization length change. The cases of single and two-color cases $D = 1, 2$ have been discussed in [5–12], noting that the localization length of a wave packet increases as the driving frequencies decrease. We make use of the Floquet representation, Fourier analysis and Bessel function theory, and argue that the localization length substantially increases, but stays finite, for any finite number of drives D. Moreover, we obtain analytic estimates of the localization length that depend on the driving frequencies, the driving strength, and the disorder strength. The equations of motion read

$$i\dot{\psi}_l = \epsilon_l(t)\psi_l - \lambda(\psi_{l+1} + \psi_{l-1}) \ , \qquad (1)$$

$$\epsilon_l(t) = \epsilon_l \left[1 + \sum_{i=1}^{D} \mu_i \cos(\omega_i t + \phi_l^i) \right]. \qquad (2)$$

The onsite energies ϵ_l are random uncorrelated numbers with the distribution $\mathcal{W}(|\epsilon| \leq W/2) = 1/W$ and $\mathcal{W}(|\epsilon| > W/2) = 0$. λ controls the hopping strength, while μ_i, ω_i and ϕ_l^i are the amplitude, frequency and phase offset of the i-th color. The incommensurate frequencies $\Omega = (\omega_i)_{i=1}^D$ satisfy $\mathbf{k} \cdot \Omega \neq 0$, for all $\mathbf{k} \in \mathbb{Z}^D \setminus \{0\}$. The random phases ϕ_l are uncorrelated numbers with the distribution $\mathcal{W}(-\pi < \phi \leq \pi) = (2\pi)^{-1}$ and break time reversal symmetry. Using Floquet expansion and properties of the Bessel functions, equations (1),(2) are mapped onto a $(D+1)$-dimensional time independent eigenvalue problem

$$\begin{aligned} E c_{l,\mathbf{v}} &= (\epsilon_l + \Omega \cdot \mathbf{v}) c_{l,\mathbf{v}} \\ -\lambda \sum_{\mathbf{s}} &\left[\mathrm{e}^{i\mathbf{s}\cdot\Phi_l^-} \mathcal{J}_{\mathbf{s}}^- c_{l-1,\mathbf{v}-\mathbf{s}} + \mathrm{e}^{i\mathbf{s}\cdot\Phi_l^+} \mathcal{J}_{\mathbf{s}}^+ c_{l+1,\mathbf{v}-\mathbf{s}} \right] , \end{aligned} \qquad (3)$$

where $\mathbf{s}, \mathbf{v} \in \mathbb{Z}^D$ and $\Phi_l^\pm = (\varphi_{l,i}^\pm)_{i=1}^D$, and the coefficients

$$\begin{aligned} \tan \varphi_{l,i}^\pm &= -\frac{\epsilon_{l\pm1} \sin \theta_{l,i}^\pm}{\epsilon_l - \epsilon_{l\pm1} \cos \theta_{l,i}^\pm} \ , \\ \mathcal{J}_{\mathbf{s}}^\pm &= \prod_{i=1}^{D} J_{s_i}(\Delta_{l,i}^\pm) \ , \\ \Delta_{l,i}^\pm &= \frac{\mu_i}{\omega_i} \sqrt{\epsilon_l^2 + \epsilon_{l\pm1}^2 - 2\epsilon_l \epsilon_{l\pm1} \cos \theta_{l,i}^\pm} \ , \end{aligned} \qquad (4)$$

depend on the random phase difference $\theta_{l,i}^\pm = \phi_l^i - \phi_{l\pm1}^i$ for $i = 1, \ldots, D$. The resulting lattice eigenvalue problem Eq.(3) has one direction in real space, and D directions in the momentum space with zero hopping along them.

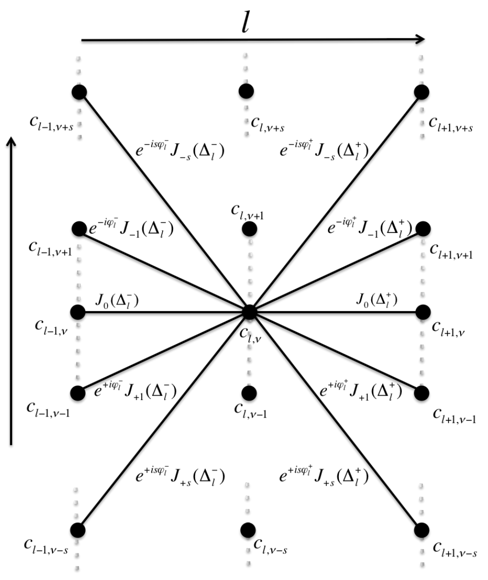


Figure 1: Time-independent eigenvalue problem Eq.(3) in the single color case $D = 1$.

In the *undriven* case $\mu_i = 0$, Eq.(3) reduces to a set of one-dimensional independent eigenvalue problems of the one-dimensional Anderson model. In the *driven* case $\mu_i \neq 0$ instead, the one-dimensional chains are coupled into a network with connections between each lattice site $c_{l,\mathbf{v}}$ and its nearest neighbor sites $c_{l\pm1,\mathbf{v}-\mathbf{s}}$ through matrix elements whose strength is given by the complex hopping coefficients $e^{i\mathbf{s}\cdot\Phi_l^{\pm}}\mathcal{J}_{\mathbf{s}}^{\pm}$. The effective number and the strength of the connections depend respectively on the ratio of the difference in the onsite energies $|\epsilon_l - \epsilon_{l\pm1} + \Omega\cdot\mathbf{s}|$ and the hopping strength $|\mathcal{J}_{\mathbf{s}}^{\pm}|$. It follows that for each color the number of channels $\mathcal{L}_i$ (connectivity) amounts to [4]

$$\mathcal{L}_i \sim \frac{2\mu_i W}{\omega_i}\,. \tag{5}$$

The single channel regime is reached when $2\mu_i W < \omega_i$. In the opposite multichannel regime we identify two cases of weak and strong driving. For weak driving, all connected sites have onsite energy difference of the order of W. Each channel has an effective disorder strength $W_{eff} = \frac{W^{3/2}}{\lambda}\sqrt{\frac{\mu_i\pi}{2\omega_i}}$ [4] which leads to a frequency independent localization length ξ as long as $W_{eff} < 10$ and to an increase of $\xi \sim 1/\omega$ for smaller frequencies. The predicted plateau is observed for $D = 1, 2$ through a measurement of the second moment of a wave packet which spreads and saturates at sufficiently large simulation times, as shown in Fig.2.

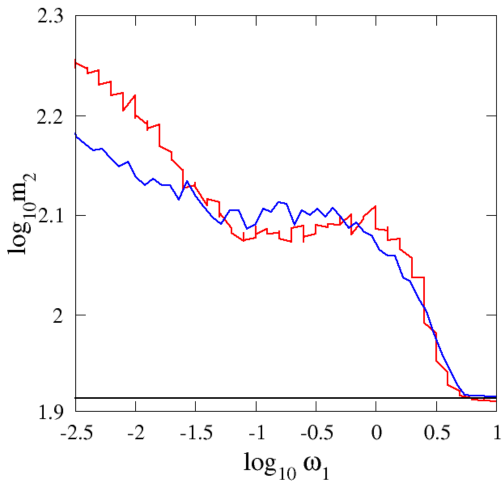


Figure 2: Second moment m_2 at $t = 10^5$ versus the driving frequency ω_1 for driving strengths $\mu_1 = \mu_2 = 0.05$ and $\omega_2 = \sqrt{2}\omega_1$. $D = 1$ (blue), $D = 2$ (red), and undriven case (black).

For strong driving, neighbouring sites in real space always allow for an optimal Floquet path for which the onsite energy difference is of the order of ω. In this case, the localization length is predicted to diverge faster with loewring the frequencies according to $\xi \sim 1/\omega^{3/2}$ [4].

For the general case of D driving terms, assuming that all frequency components satisfy the same condition of multi-channel regimes (either strong or weak driving), we find that the localization length of the model ζ_D will be of the order of $\zeta_D \sim D\zeta$ with ζ being the corresponding single color localization length. Therefore the localization length will stay finite for any finite number of colors. The limit $D \to \infty$ implies the loss of quasiperiodicity of the driving and the arise of an effective random driving, which leads to dephasing and a consequent divergence of ζ_D, in agreement with [2,3].

[1] P.W. Anderson, Phys. Rev. **109**, 1492 (1958).

[2] K. Rayanov, G. Radons and S. Flach, Phys. Rev. E **88** 012901 (2013).

[3] T. Nakanishi, T. Ohtsuki, and T. Kawarabayashi, J. Phys. Soc. Jpn. **66**, 949 (1997).

[4] H. Hatami, C. Danieli, J. D. Bodyfelt, and S. Flach, Phys. Rev. E **93**, 062205 (2016).

[5] H. Yamada, K. S. Ikeda, and M. Goda, Phys. Lett. A **182**, 77 (1993).

[6] H. Yamada, and K. S. Ikeda, Phys. Lett. A **248**, 179 (1998).

[7] H. Yamada, and K. S. Ikeda, Phys. Rev. E **59**, 5214 (1999).

[8] D.F. Martinez, and R.A. Molina, Phys. Rev. B **73**, 073104 (2006).

[9] Victor A. Gopar and Rafael A. Molina, Phys. Rev. B **81**, 195415 (2010).

[10] T. Kitagawa,T. Oka, and E. Demler, Ann. Phys. **327**, 1868 (2012).

[11] A. Soffer,and W. Wang, Commun. Part. Diff. Eq. **28**, 333 (2003).

[12] J. Bourgain, and W. Wang, Commun. Math. Phys. **248**, 429 (2004).

[13] O. N. Dorokhov, Solid State Commun. **46**, 605 (1983).

2.2 Landau-Zener Bloch oscillations with perturbed flat bands

R. Khomeriki, S. Flach

Flat band (FB) networks are specific tight-binding translationally invariant lattices with local symmetries which ensure the existence of one (or a few) completely dispersionless bands in the spectrum. FBs have been studied in a number of lattice models [1], and recently realized experimentally with photonic waveguide networks [2, 3], exciton-polariton condensates [4, 5], and ultra-cold atomic condensates [6]. FB networks rely on the existence of compact localized eigenstates (CLS) due to destructive interference, enabled by the local symmetries of the network [7]. CLS have been recently successfully obtained in experiments with photonic waveguide networks [3] and exciton-polariton condensate networks [5], turning them into addressable states in a flat band system.

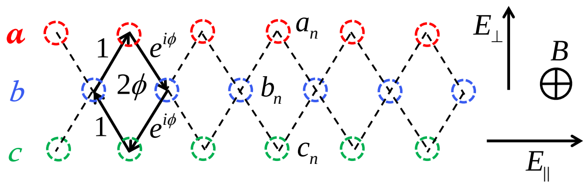


Figure 1: a) Schematics for the three leg diamond lattice with a (red) , b (blue) and c (green) legs. Dashed lines indicate sites connected with hopping (tunneling) of the quantum particle (wave). Solid arrows indicate the phase of complex hopping constants in a single plaquette due to the perpendicular (to the lattice plane) dc magnetic field B. $E_\parallel$ and $E_\perp$ define the longitudinal and transversal components of the dc electric field, respectively.

Below we answer the question whether and how CLS will perform Bloch oscillations in the presence of external fields [8]. We choose the diamond chain FB network in Fig.2. This model has an easily realizable geometry, as can be observed from published experimental realizations [2–5].

The Schrödinger equation on the FB network Fig.1 is given by

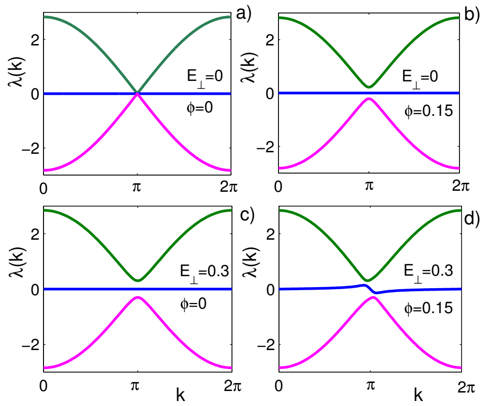


Figure 2: Band energies versus wave number. Graph a) displays the case when transversal fields are absent, in b) and c) one of the fields is present, while in graph d) both dc electric and magnetic fields are nonzero. The parameter values are indicated in the graphs.

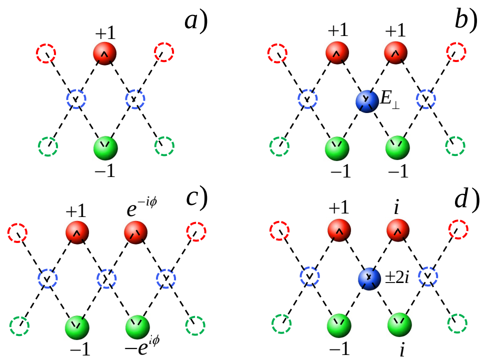


Figure 3: CLS structure. Filled circles - occupied sites with amplitudes denoted right to them. Empty circles correspond to zero amplitudes. (a) $E_\perp = \phi = 0$, $\lambda = 0$; (b) $\phi = 0$, $\lambda = 0$; (c) $E_\perp = 0$, $\lambda = 0$; (d) $E_\perp = 0$, $\phi = \pi/2$, $\lambda = \pm 2$.

$$
\begin{aligned}
i\dot{a}_n &= \left(E_\parallel n + E_\perp\right) a_n - e^{-i\phi} b_n - b_{n-1} \,, \\
i\dot{b}_n &= E_\parallel \left(n + \frac{1}{2}\right) b_n - \\
&\quad - e^{i\phi} a_n - e^{-i\phi} c_n - c_{n+1} - a_{n+1} \,, \\
i\dot{c}_n &= \left(E_\parallel n - E_\perp\right) c_n - e^{i\phi} b_n - b_{n-1} \,. \qquad (1)
\end{aligned}
$$

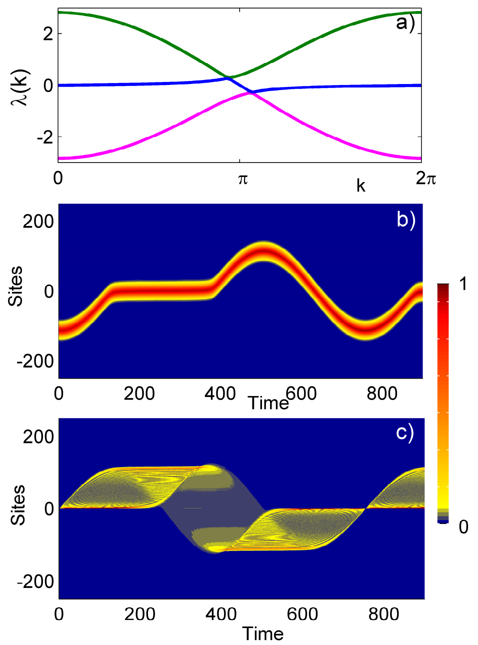


Figure 4: The case $\phi = 0.2$ and $E_\perp = \sqrt{2}\sin\phi$. a) Gapless band structure for $E_\parallel = 0$ demonstrating the complete gap closing. b) The space-time evolution of the norm density $\rho_n = |a_n|^2 + |b_n|^2 + |c_n|^2$ for a Gaussian envelope of the $k = 0$ lowest eigenenergy state from the upper panel (a). Here $E_\parallel = 0.025$. c) As in the middle panel (b), but the initial state is in the form of a pure single CLS shown in Fig.3(a).

The phase ϕ complexifies the tunneling amplitudes as a particular gauge choice for the dc magnetic (artificial gauge) field B which is oriented perpendicular to the diamond chain embedding plane. The magnetic flux penetrating each diamond plaquette has the value 2ϕ. For special cases it follows that one central (at $\lambda = 0$) band is flat and shown in Fig.2(a-c). The corresponding CLS are shown in Fig.3. Apart from those cases, all bands are nonflat, with a typical dispersion shown in Fig. 2d. The central flatband becomes dispersive, and we observe two gaps (avoided crossings) symmetrically located around $k = \pi$ and $\lambda = 0$. By fine-tuning the parameters $E_\perp$ and ϕ we can close the gaps in the band structure completely [8]:

$$E_\perp = \sqrt{2}\sin\phi\ ,\ k = \pi \pm \phi\ . \qquad (2)$$

The band structure with vanishing gaps for the particular value of $\phi = 0.2$ is shown in Fig. 4a. The perturbed flat band part still displays a significant portion which is almost dispersionless. The most striking impact of both transversal dc electric and magnetic fields in this case follows from the fact that Bloch oscillations harvest completely from Landau-Zener tunneling whose probability turns into unity. This case is displayed in Fig. 4b for an initial state given by a Gaussian envelope of the $k = 0$ lowest eigenenergy state froom Fig.4a with variance $\sigma = 70$. For a significant part of its evolution it stands still, only to cross over into a large amplitude oscillation which clearly corresponds to the scanning of the corresponding band structure with complete Landau-Zener tunneling. These features are observed even in the case of an initial condition in the form a single CLS from Fig.3(a) and shown in the lower plot in Fig.4. In this case, the CLS remains essentially frozen until it performs a violent sweep through the system over about 30 sites, where it recombines only to perform the sweep again. The combination of the physics of Bloch oscillations, Landau-Zener tunneling and of flat band networks opens promising directions for control of unconventional quantum and photonic transport through properly designed lattice structures.

[1] O. Derzhko et al, Int. J. Mod. Phys. B **29**, 1530007 (2015).

[2] D. Guzmán-Silva et al, New. J. Phys. **16**, 063061 (2014).

[3] R. A. Vicencio et al, Phys. Rev. Lett. **114**, 245503 (2015).

[4] N. Masumoto et al, New. J. Phys. **14**, 065002 (2012).

[5] F. Baboux et al, Phys. Rev. Lett. **116**, 066402 (2016).

[6] S. Taie et al, Science Advances **1**, e1500854 (2015).

[7] S. Flach et al, EPL **105**, 30001 (2014).

[8] R. Khomeriki and S. Flach, Phys. Rev. Lett. **116** 245301 (2016).

2.3 Bias-tunable giant resistance in ferromagnetic graphene vertical heterostructures with a ferroelectric thin film

Nojoon Myoung, Hee Chul Park, Seung Joo Lee

Graphene, a honeycomb-like single layer crystal of carbon atoms, has been attracting a lot of attention in the recent decade both in terms of fundamental interests and technology. Amongst the various aspects of graphene, one of the most promising potentials is that it has extraordinary transport properties such as high carrier mobility and long mean free path [1–3]. Despite these advantages for high-speed device applications, the use of single layer graphene for practical nanoelectronic devices, like field-effect transistors (FETs), is limited because of the low current on/off ratio [4–6] that implies how effectively it generates digital signals. This limitation mainly stems from the intriguing relativistic transport phenomena in graphene, so-called Klein tunneling, which results in massless and chiral Dirac fermions that can perfectly pass through electrostatic potential barriers [7–9].

Recently, an alternative platform has emerged for graphene FETs ,where graphene and other two dimensional layers are stacked vertically [10, 11]. For graphene - hexagonal boron nitride (hBN) - graphene vertical heterostructures, the vertical current density can be largely modulated by controlling quantum tunneling through an atomically thin hBN layer via gate voltage [10, 12]. Larger current on/off ratios can be achieved by using small-bandgap layered materials as a tunneling insulator [10, 13]. Owing to the huge variety of structures and properties in vertical heterostructures of 2D materials, many promising and interesting research topics have been considered, e.g., field-effect transistors [10,14], resonant tunnel diodes [15,16], and photodetectors [17,18]. In particular, the vertical heterostructure platform can also be a good candidate for graphene-based spintronics [13,19,20]. The long spin-coherent length of graphene [22–25] allows for the fabrication of spintronic devices using graphene sheets as spin transport channels, once the tunneling current is well spin-polarized through the vertical heterostructures.

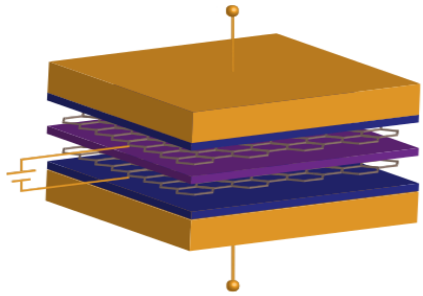


Figure 1: Model of heterostructure and electronic properties of ferromagnetic graphene (FMG).

Our results establish that an FMG vertical heterostructure is a potential platform for graphene-based spintronic devices. We demonstrated that tunneling current density can be spin-polarized through FMG-NI-FMG heterostructures, reaching up to unity. By using the spin-resolved band model of FMG, we revealed that vertical transport is accordingly spin-resolved. The spin transport through the FMG-NI-FMG heterostructure depends on the position of the equilibrium chemical potential, and its spin-polarization of the current density is tunable via gate voltage. In particular, in the vicinity of the FMG spin-resolved band gaps, there is a very drastic change in the spin-polarization between $P_j = -1$ and $+1$, leading to the gate-tunable spin-switching effects. This gate-tunable spin transport is attributed to the presence of the purely spin-polarized states in the FMG band model, which can be a good building block for GMR devices.

Accordingly, we demonstrated that the FMG heterostructure can be utilized to generate GER by replacing the NI with an FEI. While the FMG spin configuration is always parallel for FMG-NI-FMG heterostructures, having an FEI layer instead of an NI enables anti-parallel spin configuration for specific gate voltages due to the FEI-induced shift of the FMG bands. In the presence of the FEI layer between FMGs, the spin configuration is able to be manipulated by means of electric fields via bias voltage. With such a 'magnetic-field free' manipulation of the spin configuration, a giant resistance is achieved by controlling electric fields, contrary to GMR. Thus, GER has been proposed in this study through the investigation of FMG-FEI-FMG heterostructures.

As the proposed system has been theoretically studied in the absence of the external magnetic fields, there could be an interesting question about the direction of the magnetization of FMGs. In this study, the orientation of the FMG magnetization does not affect the results as two identical FMG layers were used for the proposed heterostructures. Although the magnetization is oriented along a preferable direction, the configuration of the magnetization should be parallel for FMG-NI-FMG heterostructures and either parallel or anti-parallel for FMG-FEI-FMG heterostructures according to the gate and bias voltages.

In conclusion, the gate tunability of the spin-switching effects and the GER implies that the operation of the spintronic devices proposed in this study does not require the use of magnetic fields. The prospect of the proposed system for practical spintronic applications can be also examined with studies of temperature dependence on the results.

[1] Novoselov, K. S. *et al. Science* **306**, 666-669 (2004).

[2] Bolotin, K. I. *et al. Solid State Commun.* **146**, 351-355 (2008).

[3] Bolotin, K. I., Sikes, K. J., Hone, J., Stormer & H. L., Kim, P. *Phys. Rev. Lett.* **101**, 096802 (2008).

[4] Lemme, M. C., Echtermeyer, T. J., Baus, M. & Kurz, H. A. *IEEE Electron Device Lett.* **28**, 282-284 (2007).

[5] Meric, I. *et al. Nat. Nanotechnol.* **3**, 654-659 (2008).

[6] Kim, S. *et al. Appl. Phys. Lett.* **94**, 062107 (2009).

[7] Katsnelson, M. I., Novoselov, K. S. & Geim, A. K. *Nat. Phys.* **2**, 620-625 (2006).

[8] Beenakker, C. W. *Rev. Mod. Phys.* **80**, 1337 (2008).

[9] Stander, N., Huard, B. & Goldhaber-Gordon, D. *Phys. Rev. Lett.* **102**, 026807 (2009).

[10] Britnell, L. *et al. Science* **335**, 947-950 (2012).

[11] Georgiou, T. *et al. Nat. Nanotechnol.* **8**, 100-103 (2013).

[12] Fiori, G., Bruzzone, S. & Iannaccone, G. *IEEE Electron Device Lett.* **60** 268-273 (2013).

[13] Myoung, N., Seo, K., Lee, S. J. & Ihm, G. *ACS Nano* **7**, 7021-7027 (2013).

[14] Britnell, L. *et al. Nano Lett.* **12**, 1707-1710 (2012).

[15] Britnell, L. *et al. Nat. Commun.* **4**, 1794 (2013).

[16] Mishchenko, A. *et al. Nat. Nanotechnol.* **9**, 808-813 (2014).

[17] Britnell, L. *et al. Science* **340**, 1311-1314 (2013).

[18] Yu, W. J. *et al. Nat. Nanotechnol.* **8**, 952-958 (2013).

[19] Cobas, E., Friedman, A. L., van't Erve, O. M. J., Robinson, J. T. & Jonker, B. T. *Nano Lett.* **12**, 3000-3004 (2012).

[20] Martin, M. B. *et al. ACS Nano* **8**, 7890-7895 (2014).

[21] Tombros, N., Jozsa, C., Popiniciuc, M., Jonkman, H. T. & van Wees, B. J. *Nature (London)* **448**, 571-574 (2007).

[22] Huertas-Hernando, D., Guinea, F. & Brataas, A. *Eur. Phys. J. Special Topics* **148**, 177-181 (2007).

[23] Avsar, A. *et al. Nano Lett.* **11**, 2363-2368 (2011).

[24] Kozikov, A. A., Horsell, D. W., McCann, E. & Fal'ko, V. I. *Phys. Rev. B* **86**, 045436 (2012).

[25] Guimarães, M. H. D. *et al. Phys. Rev. Lett.* **113**, 086602 (2014).

2.4 Poisson's ratio of layered two-dimensional crystals

Sung Jong Woo, Hee Chul Park, Young-Woo Son

Under uniaxial stress, Poisson's ratio defined by the ratio of the strain in the transverse direction (ϵ_t) to that of the longitudinal direction (ϵ_l), $\nu = -\epsilon_t/\epsilon_l$, measures the fundamental mechanical responses of solids against external loads [1–5]. It has strong correlation with atomic packing density, atomic connectivity [2] and structural phase transition [3–5]. The theory of elasticity allows values of Poisson's ratio of an isotropic material ranging from -1 to 0.5, i.e., from extremely compressible to incompressible materials [1,5]. Thus, when a solid is subjected to a uniaxial compression, it expands ($\nu > 0$), remains to be the same ($\nu = 0$), and shrinks ($\nu < 0$) in the transverse direction depending on the sign of Poisson's ratio. Typically, different Poisson's ratio or its sign indicates dramatic variations in mechanical properties. For example, when isothermal modulus is extremely larger than shear modulus, the material reaches its incompressible limit as shown in most liquids or rubber ($\nu \sim 0.5$) and in the opposite case, re-entrant foams and related structures show the negative ν or auxetic property [5–9]. The Poisson's ratio of common solid state crystals usually falls in the range of $0 < \nu < 0.5$ while gases and cork have $\nu \simeq 0$ [5–9].

Anisotropic materials with directional elastic properties often shows more dramatic variations in their Poisson's ratios such as the directional auxetic property [5]. In this regard, the experimental realization of graphene [10, 11], the thinnest and the strongest material [12–15], now offers a new platform to understand electronic and elastic properties of well-defined anisotropic materials and their heterostructures. Even though the Young's modulus and Poisson's ratio of graphene have been studied quite thoroughly [12–22], those along the out-of-plane direction for its few-layered forms have barely been known. Neither do for all the other available two-dimensional crystals. Since electronic properties of layered two-dimensional crystals vary a lot depending on their chemical composition as well as the number of layers [23–25], their corresponding elastic properties, especially for few layered structures, are anticipated to change accordingly. Motivated by recent rapid progress in manipulating various two-dimensional crystals and their stacking structures [24–26], we have calculated fundamental mechanical properties of three representative van der Waals (vdW) crystals along all crystallographic directions of their few-layered structures.

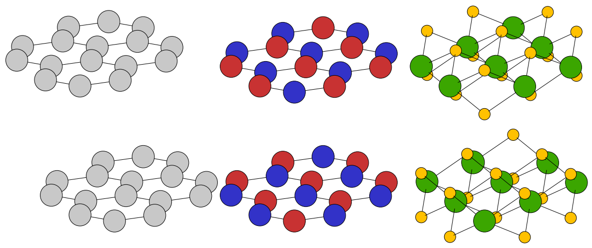


Figure 1: Lattice structures of (left) AB-stacked graphene (center) AA'-stacked h-BN and (right) 2H-MoS2. The parameter d is the interlayer distance of each structure. In 2H-MoS2, d is the vertical distance between Mo atoms in adjacent layers and d1 is the vertical intralayer sulfur-to-sulfur distance.

In this paper, we present a theoretical study using a first-principles approach on the elastic properties of layered two-dimensional crystals, including graphene, *h*-BN and 2*H*-MoS_2, in which the vdW energy is one of the governing interactions between their layers while they exhibit very different electronic properties. We find that the Poisson's ratios of graphene, *h*-BN and 2*H*-MoS_2 along out-of-plane direction are negative, near zero and positive, respectively, whereas their in-plane Poisson's ratios are all positive. The diverseness of out-of-plane Poisson's ratio is attributed to their disparate electronic properties as well as stacking structures. Thorough investigation on their elastic properties while varying the number of layers are also reported.

In conclusion, we have studied the elastic properties of multilayered two-dimensional crystals including graphene, h-BN, and $2H$-MoS_2, with interlayer van der Waals interaction properly taken into account. In-plane elastic properties are found to be barely dependent on the number of layers for all three materials. Our analysis reveals that graphene is a very peculiar axial auxetic material when inplain strain is applied. The mechanism is attributed to quantum mechanical origin rather than to structural one such as re-entrant foam. In contrast, the Poisson's ratio of h-BN with AA' stacking is found to be nearly zero and that of MoS_2 is positive.

[1] L. D. Landau, and E. M. Lifshitz, *Theory of Elasticity, 3rd Ed.*, Butterworth-Heinemann (1986).

[2] R. A. Rouxel, J. Am. Ceram. Soc. **90**, 3019 (2007)

[3] P. H. Poole, T. grande, C. A. Angell, and P. F. McMillan, Science **275**, 322 (1997)

[4] G. N. Greaves *et al.*, Science **322**, 566 (2008)

[5] G. N. Greaves, A. L. Greer, R. S. Lakes and T. Rouxel, Nat. Mat. **10**, 823 (2011) and *references therein.*

[6] R. S. Lakes, Science **235**, 1038 (1987).

[7] B. D. Caddock, and K. E. Evans, J. Phys. D. **22**, 1877 (1989)

[8] G. Milton, J. Mech. Phys. Solids, **40**, 1105 (1992)

[9] K. E. Evans, M. A. Nkansah, I. J. Hutchinson, and S. C. Rogers, Nature **353**, 124 (1991).

[10] K. S. Novoselov *et al.*, Science **306**, 666 (2004).

[11] Y. Zhang, Y.-W. Tan, H. L. Stormer, and P. Kim, Nature **438**, 201 (2005)

[12] C. Lee, X. Wei, J. W. Kysar, and J. Hone, Science **321**, 385 (2008).

[13] C. A. Marianetti and H. G. Yevick, Phys. Rev. Lett. **105**, 245502 (2010)

[14] C. Si, W. Duan, Z. Liu and F. Liu, Phys. Rev. Lett. **109**, 226802 (2012).

[15] S. J. Woo and Y.-W. Son, Phys. Rev. B **87**, 075419 (2013).

[16] S. P. Koenig, N. G. Boddeti, M. L. Dunn, and J. S. Bunch, Nanotech. **6**, 543 (2011).

[17] Y. Y. Zhang, and Y. T. Gu, Comp. Mat. Sci. **71**,197 (2013).

[18] S. A. H. Kordkheili, and H. Moshrefzadeh-Sani, Comp. Mat. Sci. **69**, 335 (2013).

[19] O. L. Blakslee, D. G. Proctor, E. J. Seldin, G. B. Spence, and T. Weng, J. App. Phys. **41**, 3373 (1970).

[20] A. Politano, A. R. Marino, D. Campi, D. Farías, R. Mirandac, and G. Chiarello, Carbon **50**, 4903 (2012).

[21] F. Scarpa, S. Adhikari, and A. S. Phani, Nanotech. **20**, 065709 (2009).

[22] M. Liu, and F. Liu, Nanotech. **25**, 135706 (2014).

[23] K. S. Novoselov *et al.*, Proc. Natl. Acad. Sci. USA **102**, 10451 (2005)

[24] A. K. Geim, and K. S. Novoselov, Nat. Mat. **6**, 183 (2007)

[25] A. K. Geim, I. V. Grigorieva, Nature **499**, 419 (2013).

[26] C. Dean *et al.*, Sol. Stat. Comm. **152**, 1275 (2012).

2.5 Operation of a semiconductor microcavity under electric excitation

D.V. Karpov, I.G. Savenko

We have developed a microscopic theory for the description of the bias-controlled operation of an exciton-polariton - based heterostructure, in particular, the polariton laser. Combining together the Poisson-like equations for the scalar electric potential and Fermi quasi-energies of electrons and holes in a semiconductor heterostructure, the Boltzmann equation for the incoherent excitonic reservoir and the Gross-Pitaevskii equation for the exciton-polariton mean field, we simulate the dynamics of the system minimising the number of free parameters and for the first time build a theoretical threshold characteristics: number of particles vs applied bias. This approach, which also accounts for the nonlinear (exciton-exciton) interaction, particle lifetime, and which can, in principle, account for any relaxation mechanisms for the carriers of charge inside the heterostructure or polariton loss, allows to completely describe modern experiments on polariton transport and model new devices.

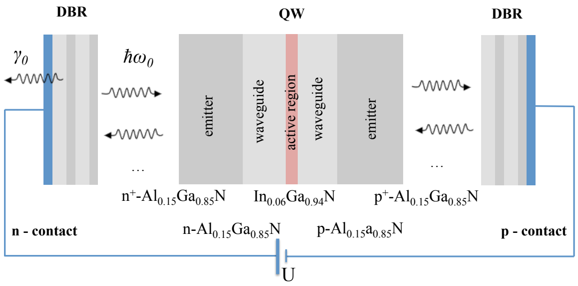


Figure 1: Growth stack for InGaN quantum-well (QW) microcavity under electrical excitation. The photons are localised between two Distributed Bragg Reflectors (DBRs) forming a single-mode cavity with frequency ω_0; the excitons are localised in the active region. γ_0 is the radiative losses rate. Electrical pumping with voltage U is employed to excite the system through bias applied to n-p contacts.

We consider a microcavity with the growth direction of the heterostricture along the axis z and EPs moving in the xy plane, see Fig. 1, thus the 3D coordinate is given by $\mathbf{r} = (x, y, z) = (\mathbf{r}_\|, z)$. For the electric potential, ϕ, we can write the Poisson equation in the form

$$\frac{\partial \phi(\mathbf{r}, t)}{\partial t} = -\nabla^2 \phi(\mathbf{r}, t) - \frac{\rho(\mathbf{r}, t)}{\epsilon(\mathbf{r})\epsilon_0}, \tag{1}$$

where $\epsilon(\mathbf{r})$ is a dielectric permittivity, $\rho = q(N_D^+ - N_A^- + p - n)$ is the charge density (here and in the following we omit the explicit notation '$(\mathbf{r}, t)$' in $\rho(\mathbf{r}, t)$, $n(\mathbf{r}, t)$ etc for breivity). N_D^+ and N_A^- being ionised donor and acceptor impurity concentrations, $N_D^+ = N_D[1 + g_D \exp(\frac{F_n - E_C + E_D + q\phi}{k_B T})]^{-1}$, $N_A^- = N_A[1 + g_A \exp(\frac{E_V + E_A - F_p - q\phi}{k_B T})]^{-1}$ with N_D and N_A being the full donor and acceptor impurity concentrations; $g_D = 2$, $g_A = 4$ are the donor and acceptor impurity degeneracy factors, respectively [2]. E_D, E_A are the ionization potentials. Further, E_C and E_V are the energies of the conduction band bottom and the valence band top. $F_n = F_n(\mathbf{r}, t)$ and $F_p = F_p(\mathbf{r}, t)$ are the Fermi quasi-energies of electrons and holes. n and p are the electron and hole densities. They read the Fermi statistics and are given by

$$\begin{aligned} n &= N_C \mathcal{F}_{1/2}\left(\frac{F_n - E_C + q\phi}{k_B T}\right), \\ p &= N_V \mathcal{F}_{1/2}\left(\frac{E_V - F_p - q\phi}{k_B T}\right), \end{aligned} \tag{2}$$

where N_C and N_V are the densities of states in the Conduction and Valence bands, correspondingly. $N_C = 2(m_n k_B T/2\pi\hbar^2)^{3/2}$ with m_n the electron effective mass; and usually $N_V = (m_{lh} k_B T/2\pi\hbar^2)^{3/2} + (m_{hh} k_B T/2\pi\hbar^2)^{3/2}$. However, since polaritons are usually based on the excitons formed of heavy holes, we assume $N_V = (m_{hh} k_B T/2\pi\hbar^2)^{3/2}$ thus neglecting the light hole component. $\mathcal{F}_\nu(\xi) = \Gamma^{-1}(\nu + 1)\int_0^\infty x^\nu dx/(1+\exp(x-\xi))$ is the Fermi integral of the order ν, $\Gamma(x)$ is the Gamma-function. In what follows, we will assume that the electron-hole subsystem of the whole system reaches the steady state much faster than the excitonic and polaritonic susbystems, which is a good approximation in most of real situations. It allows us to consider static electric potential, putting $\partial_t \phi = 0$ in (1).

Now, the key missing ingredient is the spatial distribution of the Fermi quasi-energies. In order to find them, let us use:

$$\begin{aligned} \nabla(\mu_n n \nabla F_n) &= -q(G-R), \\ \nabla(\mu_n n \nabla F_p) &= +q(G-R). \end{aligned} \tag{3}$$

where μ_n, μ_p are the carrier mobilities, G is the carriers generation and R is the general recombination rates.

Together, Eqs. (1), (2), and (3) represent a closed consistent system of equations and fully describe the electron-hole dynamics with proper boundary conditions with the boundary condition

$$F_n(z=0) - F_p(z=L) = qU. \tag{4}$$

In our work the only source of pumping is the applied bias, thus we assume $G = 0$.

The next crucial step is to connect the free charges with the formation of excitons. This we do by the dynamic equations,

$$\frac{\partial n_X(\mathbf{r}_\parallel, t)}{\partial t} = W\ \tilde{n}\ \tilde{p} - \frac{n_X}{\tau_X} - \gamma\ n_X |\psi(\mathbf{r}_\parallel, t)|^2, \tag{5}$$

where n_X is the occupation of the reservoir of excitons, W is the rate of exciton formation from the electron-hole plasma, $\tilde{n}$ and $\tilde{p}$ are the densities of electrons and holes which reside in the quantum wells of the heterostructure, and γ is the rate of polariton formation fed by the excitonic reservoir. Now we can denote the term R from Eq. (3), $R = W\ \tilde{n}\ \tilde{p}$. Thus it accounts for the electron and hole losses due to exchange with the excitonic reservoir. It should be noted, that R can account for various mechanisms of the particle loss. For instance, the non-radiative recombination can be described by the term $\tilde{R} = \tilde{n}\ \tilde{p}(1 - \exp[(Fp - Fn)/k_B T])\ [\tau_p n + \tau_n p]^{-1}$, where $\tau_{n,p}$ are the non-radiative lifetimes of the carriers of charge [3]. Besides, the recombination on dislocation cores [4] and the Auger recombination can be accounted for.

EPs we describe within the mean field approximation, using the macroscopic wave function $\psi(\mathbf{r}_\parallel, t)$ [5] and find the threshold characteristics, see Fig. 2.

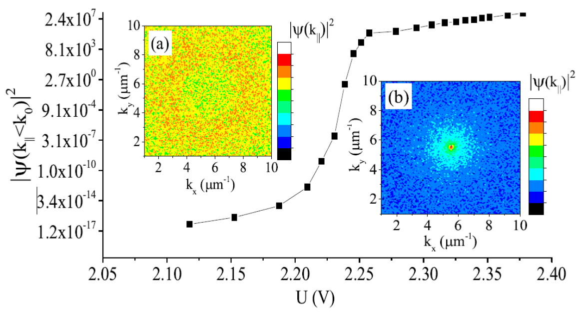


Figure 2: Threshold characteristic: (a) exciton-polariton density in the vicinity of $k_\parallel = 0$ as a function of forward bias, U, for the InGaN quantum-well diode presented in Fig. 1. The Bose-Einstein condensation starts at around $U = 2.23$ V in k_0 vicinity around 0 in k-space (in our modelling we choose k_0=2 μm^{-1}). On the bottom panels, the colormaps of the particle distribution in momentum space for different voltages are presented (b) $U = 2.2$ V (under threshold) and (c) $U = 2.3$ V (above threshold).

[1] D. V. Karpov and I. G. Savenko, Operation of a semiconductor microcavity under electric excitation, *Appl. Phys. Lett.* **109**, 061110 (2016).

[2] H. Morkoc, Handbook of Nitride Semiconductors and Devices, V. 2: Electronic and Optical Processes in Nitrides, papers 132-135, Wiley, Weinheim, 2008, 883 pages, ISBN: 352740838X.

[3] S.Yu. Karpov and Yu.N.Makarov, Dislocation Effect on Light Emission Efficiency in Gallium Nitride, *Appl. Phys. Lett.* **81**, 4721 (2002).

[4] W. Shockley and W.T. Read, Statistics of the Recombinations of Holes and Electrons, *Phys. Rev.* **87**, 835 (1952).

[5] I. G. Savenko, T. C. H. Liew, and I. A. Shelykh, Stochastic Gross-Pitaevskii Equation for the Dynamical Thermalization of Bose-Einstein Condensates, *Phys. Rev. Lett.* **110**, 127402 (2013).

2.6 Compact localized states and flatband generators in one dimension

W. Maimaiti, A. Andreanov, Hee Chul 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.

At variance with the spatially continuum case of a two-dimensional electron gas with Landau levels of the time-reversal symmetry broken quantum Hall effect, FB networks can co-exist with time reversal symmetry, and essentially rely on destructive interference. The latter 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.

So far, several approaches to construct FB networks have been proposed using graph theory , local cell construction , so-called " *Origami rules*" in decorated lattices , and repetitions of mini-arrays . None of them provides a systematic classification of FBs, and can only be considered as a partial accomplishing of a FB generator lacks in completeness. 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

$$\mathcal{H}\Psi = E\Psi \qquad (1)$$

$$\sum_{m=-\infty}^{\infty} H_m \vec{\psi}_{n+m} = E\vec{\psi}_n \,, \qquad (2)$$

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 $n \to n+p$. 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 following problem:

$$\mathcal{H}_U \Psi = E\Psi \qquad (3)$$

$$\mathcal{H}_U = \begin{pmatrix} H_0 & H_1 & H_2 & H_3 & \dots & H_U \\ H_1^\dagger & H_0 & H_1 & H_2 & \dots & H_{U-1} \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & & & & & \vdots \\ H_{U-1}^\dagger & \dots & H_2^\dagger & H_1^\dagger & H_0 & H_1 \\ H_U^\dagger & \dots & H_3^\dagger & H_2^\dagger & H_1^\dagger & H_0 \end{pmatrix} \qquad (4)$$

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

$$\sum_{m=-m_c}^{m_c} H_m \vec{\psi}_{p+m} = 0 \,,\ \vec{\psi}_{l\leq 0} = \vec{\psi}_{l>U} = 0 \qquad (5)$$

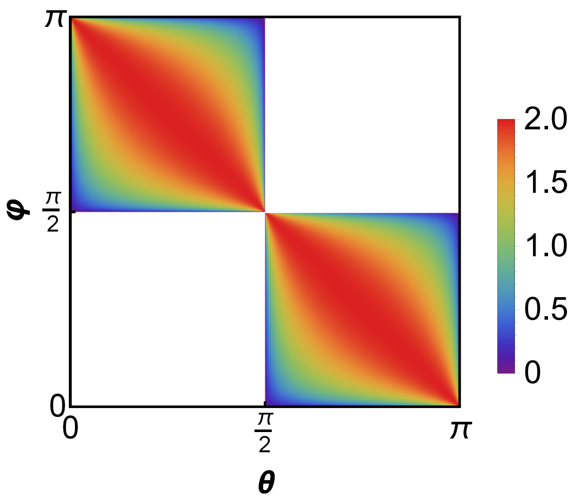
for all integers p with $-m_c + 1 \leq p \leq 0$ and $U + 1 \leq p \leq U + m_c$. Similar equations hold for $H_m^\dagger$. These two sets of equations ensure $\vec{\psi}_{l\leq 0} = \vec{\psi}_{l>U} = 0$. Then the Hamiltonian has a FB of class U. Given a network Hamiltonian, and successively increasing the test value for $U = 1, 2, \dots$ 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 (4-5). The Hermitian H_0 is an input parameter: it can be assumed diagonal, with the lowest eigenvalue shifted to 0 and the second lowest eigenvalue rescaled to 1. 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 (5) 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:

$$H_1 = \alpha \begin{pmatrix} \cos\theta\cos\varphi & e^{i\gamma}\cos\theta\sin\varphi \\ e^{-i\delta}\sin\theta\cos\varphi & e^{-i(\delta-\gamma)}\sin\theta\sin\varphi \end{pmatrix} \,, \qquad (6)$$

Solving (4-5), we have found that FB exist for any phases $\gamma = \delta$, specific values of $|\alpha|(\theta,\phi)$ and values of θ, ϕ shown on the Figure below. Interestingly, though the FB hoppings are finedtuned, they form a continuous manifold in the space of hopping matrices H_1.



This construction extends easily to larger values of ν and m_c, the main challenge being to find the most convenient parametrization of the hopping matrices H_m.

[1] Derzhko, Oleg and Richter, Johannes and Maksymenko, Mykola, Int. J. Mod. Phys. B 29, 1530007 (2015).

[2] Mielke, A., J. Phys. A: Math. Gen. 24, 3311 (1991).

[3] Flach, S. and Leykam, D. and Bodyfelt, J.D. and Matthies, P. and Desyatnikov, A. S., EPL 105, 30001 (2014).

2.7 Restoring Whispering Gallery Modes in Deformed Dielectric Cavities via Transformation Optics

Yushin Kim, Soo-Young Lee, Jung-Wan Ryu, Inbo Kim, Jae-Hyung Han, Heung-Sik Tae, Muhan Choi, Bumki Min

In dielectric cavities with rotational symmetry, whispering gallery modes (WGMs) with an extremely long lifetime can be formed by total internal reflection of light around the rim of the cavities. The ultrahigh Q-factor of WGMs has enabled a variety of impressive photonic systems, such as ultralow threshold microlasers [1–3], bio-sensors with unprecedented sensitivity [4, 5], and cavity optomechanical devices [6]. However, the isotropic emission of WGMs, which is due to the rotational symmetry, is a serious drawback in applications requiring directional light sources. Considerable efforts have thus been devoted to achieving directional emission by intentionally breaking the rotational symmetry [7–9]. However, all the methods proposed to date, have suffered from substantial Q-spoiling. Here, we show how the mode properties of dielectric cavities, such as Q-factor and emission directionality, can be tailored at will using transformation optics.

We start with a deformed boundary the so-called Pascal's limaçon which reads in polar coordinates, $r(\theta) = 1 + 2\alpha\cos\theta$, where α is a deformation parameter. The corresponding conformal transformation, which maps the unit circle to the limaçon, is given by

$$z = \beta(w + \alpha w^2) \qquad (1)$$

where w and z are complex variables that denote positions in the two complex planes respectively, and β is a positive scale factor. Figure 1 (a) and (b) show that a uniform grid in the w-plane ($w = u + iv$) can be transformed into a curved grid in the z-plane ($z = x + iy$) according to Eq. (1). It is worth pointing out that, although a straight ray trajectory inside the circle on the w-plane is mapped to a curved trajectory in the z-plane, the incident angle ξ of a ray in w-plane is preserved in the z-plane, which is an intrinsic property of conformal mapping. Therefore, the incident angle at every reflection in the limaçon cavity is kept constant, and it provides us with a classical ray picture for restoring WGMs in the conformally deformed microcavity. With this conformal mapping, an inhomogeneous cavity can be defined by imposing spatially-varying refractive indices derived from transformation optics theory.

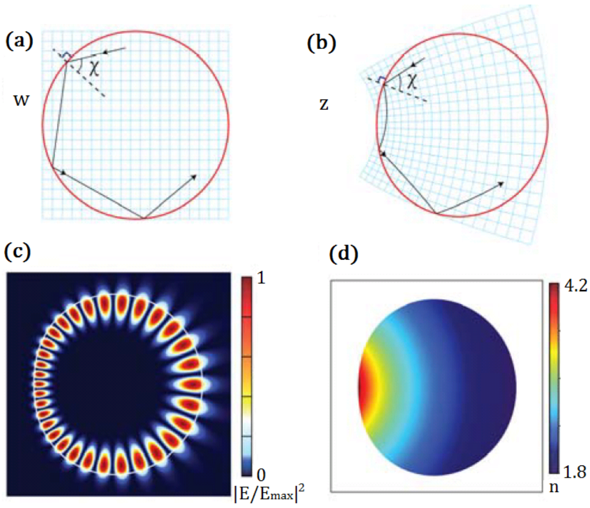


Figure 1: Homogeneous disk vs. limaçon-shaped transformation cavity. (a) A ray trajectory in the (u, v)-plane, i.e., a homogeneous disk cavity in the original space, is shown. (b) Space distortion in the (x, y)-plane and the limaçon-shaped cavity with a curved ray trajectory, generated by conformal mapping (Eq. (1)) with $\alpha = 0.2$. (c) Restored WGM (cWGM) in the limaçon-shaped cavity with the spatially varying refractive index shown in (d).

First, let us consider a homogeneous dielectric disk cavity of unit radius, as shown in Fig. 1 (a). The resonance modes in the disk cavity on the w-plane can be obtained easily by solving the Helmholtz equation with an outgoing boundary condition, where the refractive index of the disk cavity is taken as $n_0 = 1.8$. Next, we want to obtain the corresponding mode in the inhomogeneous limaçon cavity on the z-plane, described by the conformal mapping Eq. (1) with $\alpha = 0.2$ and $\beta = 0.714$, as shown in Fig.

1 (b). The resonance modes of our concern are solutions of the Helmholtz equation

$$[\nabla^2 + n^2(x,y)k^2]E(x,y) = 0 \qquad (2)$$

where ∇^2 is the 2D Laplacian and $E(x,y)$ is the normal component of the electric field with respect to the cavity plane (z plane), k is the free space wavenumber and the refractive index $n(x,y)$ is $n_0\,|dz/dw|^{-1}$ inside the cavity and 1 outside the cavity. The only difference from the case of a homogeneous disk cavity in the w plane is the introduction of the gradually varying refractive index profile $n(x,y)$ inside the cavity on the z plane, given by the ratio between the local length scales in both planes. In our cavity model, the conformal mapping is applied only to the inside of the cavity, and a uniform refractive index of $n_{out} = 1$ is assigned to the outside region of the cavity on the z plane. Related to this uniform setting of $n_{out} = 1$, a condition is needed to ensure total internal reflections in the conformally deformed cavity, that is, $|dz/dw|^{-1} \geq 1$ and, in our case, the condition is given by $\beta \leq \beta_{max} = \frac{1}{\sqrt{1+4\alpha(1+\alpha)}}$. Hereafter, the cavity defined in this way will be called the *transformation cavity* [10]. The internal field pattern of a high-Q resonance solution in the transformation cavity would be nearly the same as that of the counterpart because the condition for total internal reflection is still fulfilled in the transformation cavity. Meanwhile, the emission directionality of the transformation cavity can deviate substantially from that of the transformed counterpart due to the spatial variation of the output coupling at the dielectric–air interface, which arises from the uniform setting of $n_{out} = 1$ outside the cavity.

The intensity pattern of a high-Q mode can be calculated through a mode matching method based on a virtual space Green's function by introducing an auxiliary space that is derived from the transformation cavity via conformal mapping. The calculated intensity pattern is shown in Fig. 1 (c), where the following parameters are used: $n(x,y)$ with $n_0 = 1.8$, $\alpha = 0.2$ and $\beta = \beta_{max}$. Henceforth, we will call this kind of mode a conformal WGM (cWGM) because the incident angle of the light ray is invariant inside the cavity. The field intensity of the cWGM is localized near the boundary, as in the conventional WGM. The length scale inside the cavity varies in accordance with the refractive index $n(x,y)$ (Fig. 1 (b) and (d)) and the distance between the adjacent nodes in the intensity pattern of the cWGM therefore scales down in the high-refractive-index region of the cavity. This is the characteristic feature of cWGMs that is distinct from the conventional WGMs. Finally, we confirmed the maintenance of Q-factors, satisfaction of total internal reflection conditions, directional far field patterns, and experimental realizations of cWGMs [10].

The unique properties of the cWGM, that is, the high Q factor and the emission directionality, will be essential to attain directional coherent light from ultralow threshold microlasers and to achieve extreme sensitivities in photonic bio-sensing devices with an improved free-space optical coupling. The tailored modes achieved by the proposed scheme will be able to improve the performance of cavity-based optoelectronic devices. Although we focused here on the modes of electromagnetic waves, the basic idea of our scheme could be extended to the resonance modes of various kinds of waves, such as acoustic and elastic waves.

[1] McCall, S.L., Levi, A.F.J., Slusher, R.E., Pearton, S.J. and Logan, R.A. Appl. Phys. Lett. 60, 289 (1992).

[2] Vahala, K.J. Nature 424, 839 (2003).

[3] Armani, D.K., Kippenberg, T.J., Spillane, S.M. and Vahala, K.J. Nature 421, 925 (2003).

[4] Krioukov, E., Klunder, D.J.W., Driessen, A, Greve, J. and Otto, C. Opt. Lett. 27, 512 (2002).

[5] Vollmer, F. and Arnold, S. Nat. Methods 5, 591 (2008).

[6] Schliesser, A., Riviére, R., Anetsberger, G., Arcizet, O. and Kippenberg, T.J. Nat. Phys. 4, 415 (2008).

[7] Nöckel, J.U. and Stone, A.D. Nature 385, 45 (1997).

[8] Gmachl, C. et al. Science 280, 1556 (1998).

[9] Wiersig, J. and Hentschel, M. Phys. Rev. Lett. 100, 033901 (2008).

[10] Kim, Y., Lee. S.-Y., Ryu. J.-W., Kim, I., Han, J.-H., Tae, H.-S., Choi, M. and Min, B. Nat. Phot. 10, 647-652 (2016).

2.8 A universal explanation of tunneling conductance in exotic superconductors

Jongbae Hong, D.S.L. Abergel

A longstanding mystery in understanding cuprate superconductors is the inconsistency between the experimental data measured by angle-resolved photoemission spectroscopy (ARPES) [1, 2] and scanning tunneling spectroscopy (STS) [3–5]. Also, STS data for strongly correlated pnictide superconductors [6] display two prominent side peaks which are much bigger than the energy scale of the superconducting gap observed by ARPES measurements [7]. Therefore, explaining the structure of tunneling conductance of SCMs is one of the most challenging and urgent subjects in condensed matter physics.

This study is to prove that the two prominent side peaks in the STS data are produced by the interplay between strong electron correlations in the sample and the non-equilibrium situation imposed by the experimental setup. An additional highlight of this study, just as important as the interpretation of the side peaks, is that we can effectively find the DOS of the specific 2D correlated superconductors under study within the fitting procedure in the theory. We obtain theoretical predictions of the tunneling conductance and the density of states of the sample simultaneously and show that for cuprate and pnictide superconductors, the extracted sample DOS is consistent with the superconducting gap measured by ARPES.

The non-equilibrium calculation of dI/dV for correlated superconductors is achieved by generalizing a theory for the non-equilibrium Kondo effect in zero-dimensional (0D) mesoscopic systems [8, 9] to the extended 2D situation. Some mathematical details are presented in the the Supplementary Materials of the published paper, but in summary, the non-equilibrium tunneling dynamics are encoded within the non-equilibrium many-body Green's function for the mediating site (MS), which is derived from the Liouville operator. Once this is known, the tunneling conductance can be computed. The advantage of using the Liouvillian approach instead of the Hamiltonian approach is the availability of a complete set of basis vectors, which is not possible in the latter case. The difficulty with the Liouvillian approach arises in the calculation of Liouville matrix elements for a specific model system. This problem can be resolved by making phenomenological assumptions or treating the unknowns as fitting parameters. However, for the Hamiltonian approach, one encounters a fundamental difficulty in obtaining a complete set of basis vectors at the beginning of the calculation and therefore progress is blocked. The DOS of the correlated superconductor is captured by the lead function and the self-energy of the Green's function which is the key quantity in calculating tunneling conductance.

In real STS experiments for cuprate superconductors, every copper atom has strong onsite repulsion U (shown in Fig. 1a). The tunneling mechanism depends on the strong U at the MS only so that the rest of the sample can then be modeled as a system of non-interacting Bogoliubov quasiparticles [1,10], as sketched in Fig. 1b. Here, an "entangled state" comprising a linear combination of two singlets (solid and dashed purple loops) accompanied by other coherent spins in the tip (blue and red dots) and the sample is formed. Now, we apply the theory to correlated superconductors and find that a DOS characteristic of a d-wave superconducting order parameter for the under-doped (UD) cuprate Bi2212 and a DOS composed of an s-wave gap and a sharp DOS barrier for the pnictide LiFeAs give a well-fitting tunneling conductance. We show the case of UD Bi2212 in Fig. 2. We use flat DOS in the high frequency region to emphasize that the side peaks are not created by features in the sample DOS. These DOS functions are shown as the green lines (right-hand axis) in Fig. 2.

The quantitative agreement up to the side peaks is almost exact, and we reproduce all the low-bias features. The peaks of the DOS are located at $\Delta_p = 17.8$meV for UD Bi2212 (Fig. 2) and $\Delta_p = 2.3$meV for LiFeAs, which are consistent with the superconducting gap reported in recent ARPES data [2,7] and correspond to the low-energy shoulders in the dI/dV. The result is natural since the Bogoliubov quasiparticles introduced in Fig. 1b describe the coherent superconducting state [1].

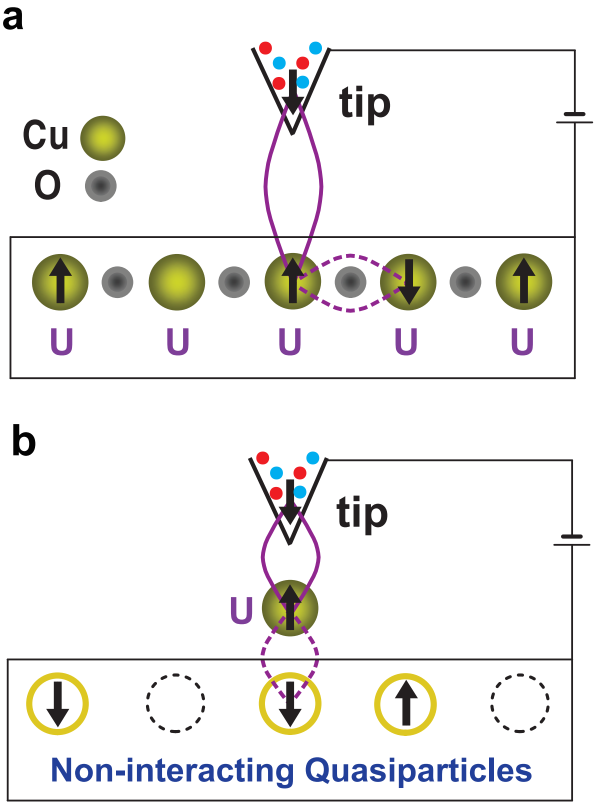


Figure 1: (a) A schematic of an STS experiment for a real cuprate superconductor. All Cu atoms have on-site repulsion U. (b) A schematic of the model. The superconductor is replaced by non-interacting Bogoliubov quasiparticles, whose DOS is that of a correlated superconductor.

We also show the dI/dV and the DOS for optimally doped (OP) and highly overdoped (HOD) cases in the insets of Fig. 2. It is noteworthy that the two side peaks in the UD and OP cases are formed in the region of flat DOS. A big difference occurs in the HOD case where strong correlation no longer persists. We obtain the HOD line shape using vanishing γ elements for a very weak effective Coulomb interaction. Note that two peaks occur within the d-wave region.

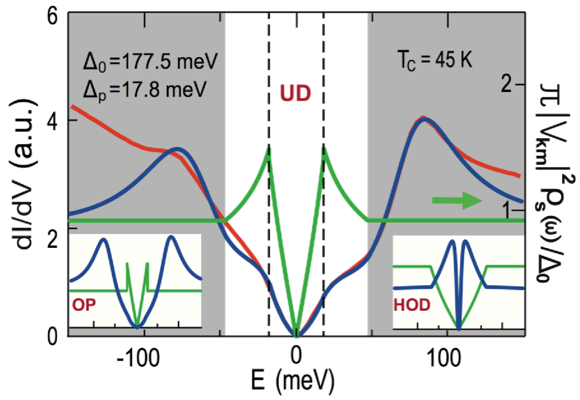


Figure 2: Comparison with STS data of cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ given in Ref. [3]. The red line is experimental data, the blue line is the prediction of our theory, and the green line (right axis) is the phenomenological sample DOS used to obtain the fit. The vertical dashed line indicates the edge of the shoulder corresponding to the peak in the sample DOS. The grey shading denotes the region of flat sample DOS. Insets: OP (left) and HOD (right) cases.

In conclusion, we show that the dI/dV curve is “not” simply a reflection of the sample DOS as it would be in the weakly interacting case, and therefore the two side peaks have nothing to do with a correlated gap in the DOS. We demonstrate that the origin of the side peak is the entangled state tunneling at steady-state non-equilibrium.

[1] Lee, W. S. *et al. Nature* **450**, 81 (2007).
[2] Tanaka, K. *et al. Science* **314**, 1910 (2006).
[3] Lawler, M. J. *et al. Nature* **466**, 347 (2010).
[4] Pushp, A. *et al. Science* **324**, 1689 (2009).
[5] Fischer, O., Kugler, M., Maggio-Aprile, I., Berthod, C. & Renner, C. *Rev. Mod. Phys.* **79**, 353 (2007).
[6] Chi, S. *et al. Phys. Rev. Lett.* **109**, 087002 (2012).
[7] Umezawa, K. *et al. Phys. Rev. Lett.* **108**, 037002 (2012).
[8] Hong, J. *J. Phys: Conden. Matt.* **23**, 225601 (2011).
[9] Hong, J. *J. Phys: Conden. Matt.* **23**, 275602 (2011).
[10] Yang, H.-B. *et al. Nature* **456**, 77 (2008).

2.9 Interacting ultracold atomic kicked rotors: dynamical localization?

Pinquan Qin, A. Andreanov, Hee Chul Park, S. Flach

The quantum kicked rotor (QKR) model is a canonical model to explore quantum chaos [1, 2]. It describes a quantum rotor degree of freedom which is periodically kicked by a force periodic in the angle. The QKR enjoys dynamical localization (DL) - i.e. the arresting of the growth of the momentum despite the absence of a cutoff in the frequency of the kick drive. This happens because classical chaotic diffusion is suppressed by quantum interference effects.

The original quantum kicked rotor corresponds to a single quantum particle problem. The effect of interactions on Anderson localization has been attracting a lot of interest recently and several theoretical studies considered various versions of interacting kicked rotors. The authors of Ref. [3] analyzed coupled relativistic rotors which might be applicable to fermions in pulsed magnetic fields, and reported that DL can be destroyed by suitable parameter tuning. In Ref. [4], the coupling was sinusoidal depending on the two rotors relative coordinates: recovering of the chaotic behavior was found above some kicking threshold in the semi-classical approximation.

From the experimental perspective, interaction between rotors is negligible for Rydberg atoms and laser-kicked molecular rotors. However the interaction between ultracold atoms in a Bose-Einstein condensate (BEC) can be substantial, and even tunable using Feshbach resonances [5], which is particularly true for sodium atoms used in Ref. [6]. The atom-atom interaction in this case is typically of a contact type, i.e. the atoms interact through a $\delta(x_1 - x_2)$ potential [5]. For the experimental realization in Ref. [6], this interaction of BEC atoms persists at all times - in contrast to the kick potential, and in contrast to the theoretical studies discussed above, which consider a kicked (time-dependent) interaction. A $\delta(x)$ interaction is long-ranged in momentum space, and can therefore have a qualitatively strong impact on DL for interacting ultracold atoms. Will DL survive, or not?

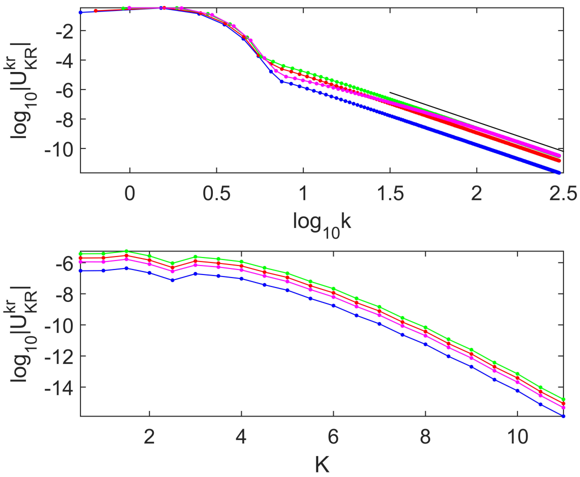


Figure 1: Kicking strength $\xi = 3$ and driving period $T = 1$. The colors correspond to different inverse interactions strengths: blue - $A_\lambda = 10$, red - $A_\lambda = 1$, green - $A_\lambda = 0.1$, magenta - $A_\lambda = 0.01$. *Top*: $\log_{10}|U^{kr}_{KR}|$ vs. $\log_{10} k$ with $K = R = 0$ and fixed r. The black line is plotted as $\log_{10}|U^{kr}_{KR}| = -4\log_{10} k - 0.2$. *Bottom*: $\log_{10}|U^{kr}_{KR}|$ vs. K with $R = 0$, fixed values of relative momenta k and r.

In this work, we provide an answer to this question. We consider two bosons interacting via a δ-function potential that are driven by a periodic kicking potential. The wave function for two δ-function interacting bosons is computed. Choosing them as the basis and considering $k \gg r \gg 1$, the matrix elements of the time evolution operator decay as

$$|U^{kr}_{KR}| \sim \frac{|\mathcal{M}_2|}{2\pi k^4 A_\lambda}\,. \qquad (1)$$

where $|\mathcal{M}_2| = |(\xi T/\hbar)J'_{2(K-R)}(2\xi T/\hbar)|$, $A_\lambda = \hbar^2/M\lambda$. Here, K, R is the center of mass momentum, k, r is the relative momentum, λ is the interaction strength, ξ is the kicking strength, T is the kicking period and M is the mass of bosons. Therefore, the matrix element $|U^{kr}_{KR}|$ decays super-exponentially fast with the center of mass K momentum, due to the scaling of $\mathcal{M}_2$. The decay along the relative momentum k direction however is a power law k^{-4}, reflecting the presence of a singular δ-function interaction. The comparison of the numerical results to the asymptotic behavior is presented in Fig. 1. The top plot shows the decay of matrix element U_{KR}^{kr} with relative momentum k for several values of the coupling A_λ indicated by colors. The power law fit $\log_{10}|U_{KR}^{kr}| = -4\log_{10} k - 0.2$ (the black line) agrees well with the numerical values of the matrix elements U_{KR}^{kr}. The bottom plot in Fig. 1 shows the decay of the matrix elements as a function of K: a faster than exponential decay is observed.

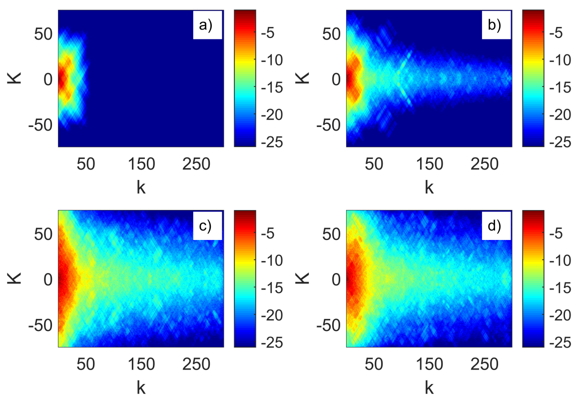


Figure 2: $\log_{10}|C_K^k(NT)|$ vs. K, k with momenta cutoffs $K_{\max} = 301$, $k_{\max} = 300$, $\xi = 3$, $T = 1$, $N = 5000$. The interaction strengths for a) to d) $A_\lambda = 10^{14}$, $A_\lambda = 10$, $A_\lambda = 0.1$, $A_\lambda = 0.01$ respectively.

As the result of this qualitative difference in the decay properties of the matrix elements, super-exponential decay of the matrix element ensures the survival of dynamical localization for the center-of-mass momentum, while the power-law decay destroys it for the relative momentum. This is our key result. The impact of the decay properties of the matrix elements of U is observed in the evolution of an initial state $|\psi(0)\rangle = |\phi_{K_0}^{k_0}\rangle$ with fixed momenta K_0 and k_0. The final state after N driving periods is $|\psi(NT)\rangle = U^N|\psi(0)\rangle = \sum_{K,k} C_K^k(NT)|\phi_K^k\rangle$. Figure 2 shows the amplitude distribution $|C_K^k(NT)|$ of the final state after $N = 5000$ driving periods for several values of A_λ. Fig. 2 (a) shows the final state for the case of two essentially non-interacting rotors ($A_\lambda = 10^{14}$). The final state is localized in both K and k momenta directions, displaying the dynamical localization of the non-interacting kicked rotor model. As the strength of the interaction is increasing, Figs. 2 (b)-(d), the final state starts to extend along the k direction, but remains localized along center-of-mass K direction. The interaction between the two rotors delocalizes the state in the relative momentum k direction.

We think, that in the many-body case, this mechanism still holds, leading to the destruction of DL, and is even more efficient due to the increased number of relaxation channels. The destruction of dynamical localization should be easily observable in setups similar to the one used in Ref. [6] using Feshbach resonances. Furthermore, while contact interaction is a good approximations, our conclusions hold for other regularized (analytic) longer ranged interactions as well, at least up to the corresponding energy cutoff which will separate the convergence criteria of the Fourier series of the contact interaction potential from its regularized version in momentum space. The extension to many interacting particles is also an interesting path. To analyze this, we need to consider many interacting atoms and study the highly complex case of many-body interactions for quantum kicked rotors. While this is still a challenging task, we refer to mean field treatments of this case in Refs. [7, 8] which demonstrate the complete destruction of dynamical localization as well.

[1] B. V. Chirikov, Phys. Rep. **52**, 263 (1979).
[2] F. M. Izrailev, Phys. Rep. **196**, 299 (1990).
[3] E. B Rozenbaum, and V. Galitski, arXiv:1602.04425.
[4] S. Adachi, M. Toda, and K. Ikeda, Phys. Rev. Lett. **61**, 659 (1988).
[5] C. Cheng, G. Rudolf, J. Paul, and T. Eite, Rev. Mod. Phys. **823**, 1225 (2010).
[6] F. L. Moore, J. C. Robinson, C. Bharucha, P. E. Williams, and M. G. Raizen, Phys. Rev. Lett. **73**, 2974 (1994).
[7] D. L. Shepelyansky, Phys. Rev. Lett. **70**, 1787 (1993).
[8] G. Gligoric, J. D. Bodyfelt and S. Flach, EPL **96**, 30004 (2011).

2.10 Nonlinear phenomenon in superfluid Fermi gases: multiple period states in optical lattices

Sukjin Yoon, Franco Dalfovo, Takashi Nakatsukasa, Gentaro Watanabe

Interplay between the nonlinearity due to the emergence of the superfluid order parameter and the periodicity of the lattice is very intriguing because these two are essential elements in condensed matter. Ultracold atomic gases in optical lattices enable us to study the subtle interplay of these effects deeply and directly (see, e.g., [1] for review) because of their high controllability of both the lattice geometry and the interatomic interaction (characterized by the s-wave scattering length a_s) (see, e.g., [2, 3]). Especially, by changing the interatomic interaction in superfluid Fermi gases using a Feshbach resonance, one can go along the crossover from the weakly coupled Bardeen-Cooper-Schrieffer (BCS) state to the Bose-Einstein condensate (BEC) state of tightly bound bosonic dimers [4–8], which allows us to study Bose and Fermi superfluids from a unified perspective.

Emergence of multiple period states, namely a class of stationary states whose period does not coincide with that of the external potential, but is a multiple of it, is a typical nonlinear phenomenon. For BECs in a periodic potential, it was found that multiple period states appear due to nonlinearity of the interaction term of the Gross-Pitaevskii (GP) equation [9]. However, these multiple period states in BECs are energetically unfavorable compared to the normal Bloch states whose period is equal to the lattice constant, and the lowest multiple period states are dynamically unstable [9].

Nonlinear phenomena in Fermi superfluids in a periodic potential [10–12] can be more important compared to those in Bose superfluids because of the wide implications for various systems in condensed matter physics and nuclear physics such as superconducting electrons in solids and superfluid neutrons in neutron stars (e.g., [13–15]). However, unlike the case of Bose gases, the study of nonlinear phenomena of superfluid Fermi gases is at a very infant stage (see, e.g., [16, 17]) and little has been studied about multiple period states in superfluid Fermi gases. Therefore, even a fundamental problem whether multiple period states exist along the BCS-BEC crossover was still open.

Under such circumstances, we have studied multiple period states in superfluid Fermi gases in [18]. In this work, we consider ultracold superfluid Fermi gases in the BCS-BEC crossover flowing through a one-dimensional optical lattice. By solving Bogoliubov-de Gennes equations, we have found that multiple period states indeed exist in Fermi superfluids (see Fig. 1), which is a consequence of the non-linear behavior of the system originated from the presence of the order parameter associated with superfluidity. We have also found that, in the BCS side of the crossover, the multiple period states can be energetically favorable compared to the normal Bloch states (see Fig 2) and their survival time against dynamical instability drastically increases (see Fig. 3), suggesting that these states can be accessible in current experiments with ultracold gases. This is in sharp contrast to the situation in BECs.

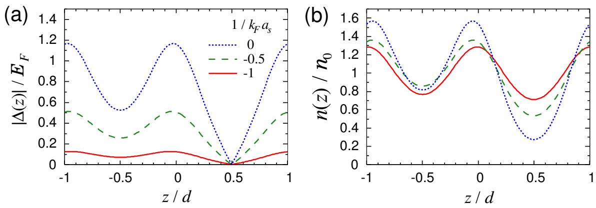


Figure 1: Profiles of (a) the magnitude of the pairing field $|\Delta(z)|$ and (b) the density $n(z)$ of the lowest period-doubled states at their first Brillouin zone edge $P = P_{\rm edge}/2$ for various values of the interaction parameter $1/k_F a_s$. In the deep BCS side ($1/k_F a_s = -1$), unlike $|\Delta(z)|$, there is no large difference in $n(z)$ between the regions of $-1 < z/d \leq 0$ and $0 < z/d \leq 1$ (d is the lattice constant). However, this difference becomes more significant with increasing $1/k_F a_s$. This figure is taken from [18].

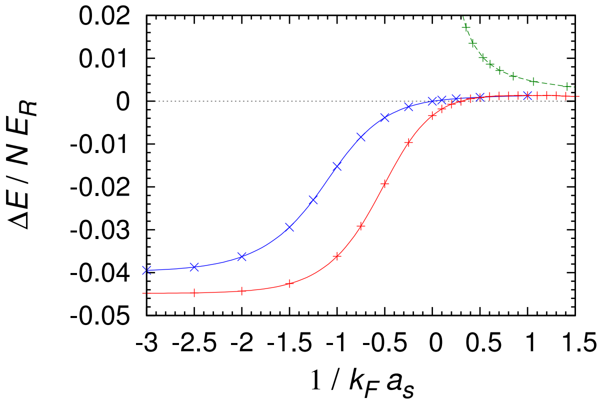


Figure 2: Difference ΔE of the energy per particle in units of the recoil energy E_R between the normal Bloch states and period-doubled states at $P = P_{\rm edge}/2$. Here we define $\Delta E \equiv E_2 - E_1$, where E_1 and E_2 represent the energy of the normal Bloch states and that of the period-doubled states, respectively. Results for two different values of the lattice strength s are shown: The red solid line with $+$ ($s = 1$) and blue solid line with $\times$ ($s = 2$) show the results obtained by solving the BdG equations and the green dashed line shows the results by the GP equation for $s = 1$. Note that, in the BCS side, the energy of the period-doubled states at $P = P_{\rm edge}/2$ is lower than that of the normal Bloch states while the latter is lower than the former in the deep BEC side. This figure is taken from [18].

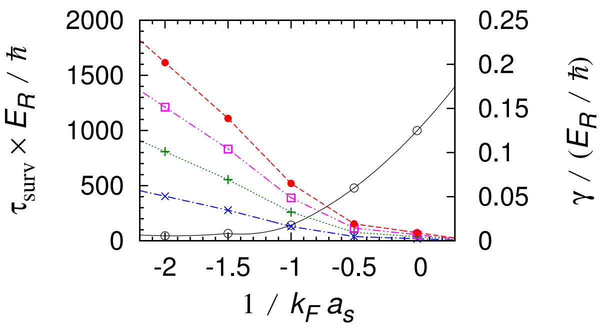


Figure 3: Growth rate γ of the fastest growing mode (black solid line) and survival time $\tau_{\rm surv}$ of the period-2 state at $P = P_{\rm edge}/2$ and $s = 1$. Blue dashed-dotted, green dotted, magenta dashed double-dotted, and red dashed lines show $\tau_{\rm surv}$ for relative amplitude of the initial perturbation of 10%, 1%, 0.1%, and 0.01%, respectively. This figure is taken from [18].

[1] G. Watanabe, B. P. Venkatesh, and R. Dasgupta, Entropy **18**, 118 (2016).

[2] C. J. Pethick and H. Smith, *Bose Einstein Condensation in Dilute Gases* 2nd edn (Cambridge University Press, Cambridge, 2008).

[3] I. Bloch, J. Dalibard, and W. Zwerger, Rev. Mod. Phys. **80**, 885 (2008).

[4] D. M. Eagles, Phys. Rev. **186**, 456 (1969).

[5] A. J. Leggett, in *Modern Trends in the Theory of Condensed Matter* (Springer-Verlag, Berlin, 1980) pp 13–27.

[6] P. Nozières and S. Schmitt-Rink, J. Low Temp. Phys. **59**, 195 (1985).

[7] C. A. R. Sá de Melo, M. Randeria, and J. R. Engelbrecht, Phys. Rev. Lett. **71**, 3202 (1993).

[8] S. Giorgini, L. P. Pitaevskii, and S. Stringari, Rev. Mod. Phys. **80**, 1215 (2008).

[9] M. Machholm, A. Nicolin, C. J. Pethick, and H. Smith, Phys. Rev. A **69**, 043604 (2004).

[10] G. Watanabe, S. Yoon, and F. Dalfovo, Phys. Rev. Lett. **107**, 270404 (2011).

[11] G. Watanabe and S. Yoon, JKPS **63**, 839 (2013).

[12] D. Yu, W. Yi, and W. Zhang, Phys. Rev. A **92**, 033623 (2015).

[13] A. Gezerlis and J. Carlson, Phys. Rev. C **77**, 032801(R) (2008).

[14] A. Gezerlis and J. Carlson, Phys. Rev. C **81**, 025803 (2010).

[15] G. Watanabe, F. Dalfovo, L. P. Pitaevskii, and S. Stringari, Phys. Rev. A **83**, 03321 (2011).

[16] M. J. H. Ku, W. Ji, B. Mukherjee, E. Guardado-Sanchez, L. W. Cheuk, T. Yefsah, and M. Zwierlein, Phys. Rev. Lett. **113**, 065301 (2014).

[17] M. J. H. Ku, W. Ji, B. Mukherjee, T. Yefsah, and M. Zwierlein, Phys. Rev. Lett. **116**, 045304 (2016).

[18] S. Yoon, F. Dalfovo, T. Nakatsukasa, and G. Watanabe, New J. Phys. **18**, 023011 (2016).

2.11 Fluctuation theorem and critical systems: emergent universality in nonequilibrium processes

Danh-Tai Hoang, B. Prasanna Venkatesh, Seungju Han, Junghyo Jo, Gentaro Watanabe, Mahn-Soo Choi

Fluctuation theorems provide universal and exact relations for nonequilibrium processes irrespective of how far a system is driven away from equilibrium. The discovery of the fluctuation theorems is a major development in nonequilibrium statistical mechanics, pioneered by Bochkov and Kuzovlev [1, 2] for a special case and thriving with the celebrated equalities of Jarzynski [8] and Crooks [9] which hold for general forcing protocols (see, e.g., [3–6] for recent reviews).

Since the discoveries of the Jarzynski equality [8] and the Crooks relation [9], a large effort has been made to find applications of these universal relations. In this work [7], we consider an application of the Jarzynski equality to study the dynamical properties of the phase transition.

Although the fluctuation theorems hold universally, they require sufficient sampling from the initial ensemble, causing a convergence problem in many situations [10–14]. For example, consider the Jarzynski equality,

$$\langle e^{-\sigma} \rangle = 1, \tag{1}$$

where $\sigma \equiv \beta(W - \Delta F)$ is the irreversible entropy production, W the work performed to the system, and β the inverse temperature. The realizations of a thermodynamic process which yield the dominant contribution to the ensemble average of $e^{-\sigma}$ can be very different from typical realizations under the same condition. Then, sufficient sampling of the dominant realizations becomes intractable with increasing system size, and in reality the Jarzynski equality is hard to verify to high accuracy with a finite number of samples.

Moreover, even in the ideal case with sufficient sampling, there are a class of processes such as the free expansion of a gas, to which the Jarzynski equality does not apply due to a fundamental reason that has been referred to as *absolute irreversibility* [15–20]. A process is called absolutely irreversible if there exists a path in phase space whose probability to occur in the forward direction is zero while that in the reverse direction is nonzero, or vice versa. A typical situation occurs when the accessible phase spaces for the system at the beginning and end of a protocol are not identical.

The central idea of this work [7] is to use the deviation from the Jarzynski equality as a "probe" instead of an error. Here, we examine the Jarzynski equality [8] for a quenching process across the critical point of second-order phase transitions, where absolute irreversibility (see Fig. 1) and the effect of finite-sampling of the initial equilibrium distribution arise in a single setup with equal significance. We consider the Ising model as a prototypical example for spontaneous symmetry breaking and take into account the finite sampling issue by introducing a tolerance parameter δ. For a sudden quench, the deviation from the Jarzynski equality evaluated from the ideal ensemble average could, in principle, depend on the reduced coupling constant ϵ_0 of the initial state and the system size L. Using the scaling theory of phase transitions and Monte-Carlo simulations, we find that this deviation exhibits a scaling behavior through a universal combination of these quantities for a given tolerance parameter (see Fig. 2), inherited from the critical scaling laws of second-order phase transitions [7]. A similar scaling law can be obtained for the finite-speed quench as well within the Kibble-Zurek mechanism [7]. This finding may provide a unique application of the fluctuation theorems to study the dynamical properties of phase transitions. This finding may provide a unique application of the FTs to study the dynamical properties of phase transitions.

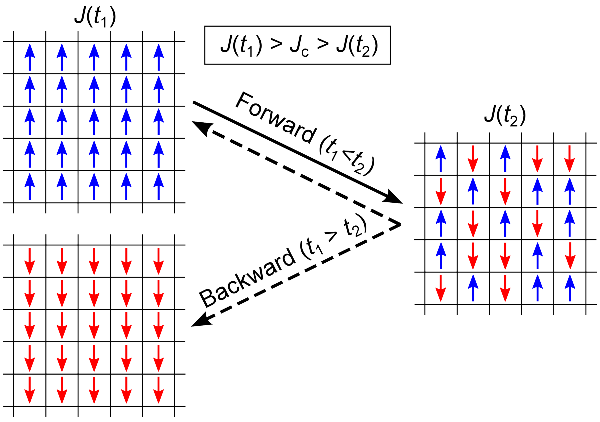


Figure 1: Schematic representation of the absolute irreversibility in the quench dynamics of Ising model. In the forward process, the system is initially at equilibrium with positive spontaneous magnetization, whereas in the backward process the initial equilibrium state has no magnetization. When the coupling J increases across the critical point, the system can have either positive or negative magnetization. The latter case has no corresponding forward path, which results in the absolute irreversibility. This figure is taken from [7].

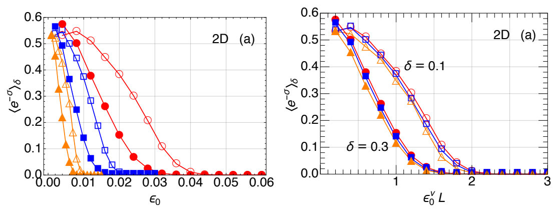


Figure 2: Scaling law in $\langle e^{-\sigma}\rangle_\delta$, which takes into account the effect of the finite sampling through the tolerance parameter δ. Left panel: $\langle e^{-\sigma}\rangle_\delta$ as a function of ϵ_0 from Monte Carlo simulations of the Ising model for a 2D square lattice with different system size L (circles: $L = 50$, squares: $L = 100$, and triangles: $L = 200$). Empty symbles and filled symbols are for the tolerance parameter $\delta = 0.1$ and $\delta = 0.3$, respectively. Right panel: The same as the top panel but as a function of the universal scaling combination $\epsilon_0^\nu L$ with ν being the critical exponent of the correlation length and ϵ_0 being the reduced coupling constant of the initial state. Note that all the lines collapse into a single line for each value of δ. This figure is taken from [7].

[1] G. N. Bochkov and Yu. E. Kuzovlev, Sov. Phys. JETP **45**, 125 (1977).

[2] G. N. Bochkov and Yu. E. Kuzovlev, Sov. Phys. JETP **49**, 543 (1979).

[3] C. Jarzynski, Eur. Phys. J. B **64**, 331 (2008).

[4] C. Jarzynski, Ann. Rev. Cond. Mat. Phys. **2**, 329 (2011).

[5] L. P. Pitaevskii, Sov. Phys. Usp. **54**, 625 (2011).

[6] U. Seifert, Rep. Prog. Phys. **75**, 126001 (2012).

[7] D.-T. Hoang, B. P. Venkatesh, S. Han, J. Jo, G. Watanabe, and M.-S. Choi, Sci. Rep. **6**, 27603 (2016).

[8] C. Jarzynski, Phys. Rev. Lett. **78**, 2690 (1997).

[9] G. E. Crooks, Phys. Rev. E **60**, 2721 (1999).

[10] D. M. Zuckerman and T. B. Woolf, Phys. Rev. Lett. **89**, 180602 (2002).

[11] J. Gore, F. Ritort, and C. Bustamante, Proc. Natl. Acad. Sci. U.S.A. **100**, 12564 (2003).

[12] C. Jarzynski, Phys. Rev. E **73**, 046105 (2006).

[13] M. Palassini and F. Ritort, Phys. Rev. Lett. **107**, 060601 (2011).

[14] A. Suárez, R. Silbey, and I. Oppenheim, Phys. Rev. E **85**, 051108 (2012).

[15] R. C. Lua and A. Y. Grosberg, J. Phys. Chem. B **109**, 6805 (2005).

[16] J. Sung, arXiv:cond-mat/0506214 (2005).

[17] D. H. E. Gross, arXiv:cond-mat/0508721 (2005).

[18] C. Jarzynski, arXiv:cond-mat/0509344 (2005).

[19] J. M. Horowitz and S. Vaikuntanathan, Phys. Rev. E **82**, 061120 (2010).

[20] Y. Murashita, K. Funo, and M. Ueda, Phys. Rev. E **90**, 042110 (2014).

Chapter 3

Details and Data

3.1 Visitors and Workshop Program

Aiming at combining the scientific research excellence with the exchange of knowledge at the highest level, PCS offers an active visitors and workshop program. As the key element of the structure of the Center, it is deciding for 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 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).

The visitors program provides support not only for guest scientists and individual visits (e.g. collaboration meetings, Ph.D. student training, sabbatical stay), but also manages the entire logistics and organization of the international workshops, seminars, colloquia, symposia, and the so-called advanced study groups (ASG). 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 PCS members and visitors, also participating actively in our seminar program. In 2016, 95 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, PCS conducts international workshops held on our premises. 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 visitors program. For future reference, we collect all the workshop presentations (invited and contributed) and post them online. For PCS members and visitors, workshops provide an excellent occasion for scientific interactions and collaborations - in addition to the lively research environment seminar with frequently held talks, ASG discussions, and regular contacts with numerous visitors.

3.1.1 Workshops

1. *Anderson Localization in Topological Insulators*
   Workshop: September 5 - 9, 2016
   Scientific coordinators: V. Kagalovsky, A. Chudnovskiy, I. Yurkevich
   39 participants from 14 countries (including 8 participants from Korea)

2. *Topological States of Light and Beyond*
   Workshop: June 20 - 24, 2016
   Scientific coordinators: A. Miroshnichenko, A. Khanikaev, H.C. Park
   40 participants from 11 countries (including 25 participants from Korea)

3. *Topology in Matter*
   Focus Workshop: November 25 - 27, 2015
   Scientific coordinator: H.C. Park
   26 participants from 2 countries (including 25 participants from Korea)

4. *Nanomechanical systems: From New Materials to New Applications*
   Workshop: July 26 - 30, 2015
   Scientific coordinators: K.-H. Ahn, A. Cleland, S. Flach, M. Kiselev
   35 participants from 7 countries (including 22 participants from Korea)

Future overview

1. *Quantum Electron Transport in Emerging 2D Materials*
   Workshop: November 25 - 26, 2016
   Scientific coordinators: H.-S. Sim, Y.-J. Doh, M.-H. Bae, M.-S. Choi, Y. Chung, K. Kang, J.-J. Kim, H.-J. Lee, H.-W. Lee, H.C. Park

2. *International Workshop on Physics of Exciton-Polaritons in Artificial Lattices*
   Workshop: May 15 - 19, 2017
   Scientific coordinators: Y. Rubo, T. Liew, I. Savenko

3. *Flat-band Networks in Condensed Matter and Photonics*
   Workshop: August 28 - September 1, 2017
   Scientific coordinators: O. Derzhko, S. Flach, J. Richter

4. *International Workshop on Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems*
   Workshop: September 18 - 22, 2017
   Scientific coordinators: A. Akbari, I. Eremin, T. Tohyama

5. *Dissipative Quantum Chaos: from semi-groups to QED experiments*
   Workshop: October 23 - 27, 2017
   Scientific coordinators: S. Denisov, I. Lesanovsky, R. Fazio

3.1.2 Advanced Study Groups

1. *Anderson Localization in Topological Insulators*
   Advanced Study Group: August 24 - September 21, 2016
   Convener: V. Kagalovsky
   Members: A. Chudnovskiy, I. Yurkevich

2. *Topological States of Light and Beyond*
   Advanced Study Group: June 20 - July 17, 2016
   Convener: A. Miroshnichenko
   Members: K. Bliokh, Y. Chong, K.-S. Kim, K.W. Kim, H.C. Park, A. Khanikaev, A. Poddubny, A. Souslov

3. *Nonergodicity in Quantum and Classical Many Body Systems*
   Advanced Study Group: May 9 - June 20, 2016
   Conveners: B. Altshuler, S. Flach
   Members: G.Y. Cho, S. Denisov, L. Faoro, S. Fishman, L. Ioffe, R. Fazio, K.-S. Kim, V. Kravtsov, E.-G. Moon, A. Politi, Y. Rubo, H.-S. Sim, W.-M. Wang, V. Yudson, E. Yuzbashyan

4. *Many Body Localization, Nonergodicity, and All That*
   Advanced Study Group: June 23 - July 31, 2015
   Conveners: B. Altshuler, S. Flach
   Members: I. Aleiner, J. Bodyfelt, R. Berkovits, S. Denisov, L. Faoro, L. Ioffe, A. Politi, E. Yuzbashyan, X. Yu

Future overview

1. *Dissipative Quantum Chaos*
   Advanced Study Group: February, August and October 2017
   Convener: S. Denisov
   Members: B. Altshuler, T.S. Cubitt, S. Diehl, A. Eckardt, I. Lesanovsky, D. Poletti, K. Zyczkowski

2. *Topological phases in arrays of Luttinger liquid wires*
   Advanced Study Group: August 28 - September 27, 2017

Convener: A.L. Chudnovskiy
Members: V. Kagalovsky, I.V. Yurkevich

3.1.3 Workshop Reports

Anderson Localization in Topological Insulators
Scientific coordinators: Victor Kagalovsky, Alexander Chudnovskiy, Igor Yurkevich

The Workshop on Anderson Localization in Topological Insulators took place at the Center for Theoretical Physics of Complex Systems, Daejeon on September 5 - 9, 2016. Its 26 invited talks covered a wide range of theoretical and experimental developments in the theory of interacting disordered fermionic systems with special emphasis on topological insulators. The topics of the talks and Poster session included:

- Disorder driven Anderson transition
- Magnetic impurities and ballistic to localized regime crossover
- Robustness of topological insulators against random multi-particle backscattering
- Spin-polarized electron injection into topological insulators
- Disorder in fractional topological insulator

Among the speakers were the leading experts in the field of topological insulators and Anderson localization. We will mention just a few outstanding talks presented at our Workshop.

- Ravindra N. Bhatt (Princeton, USA) - Disorder Driven Fractional Quantum Hall Transitions
- Rosario Fazio (ICTP, Italy) - Signatures of many-body localisation in the dynamics of two-sites entanglement
- Yuval Gefen (Weizmann, Israel) - Spontaneous Time Reversal Symmetry Breaking in Topological Insulators
- Alex Kamenev (Minneapolis, USA) - 1D Topological Anderson Insulators
- Sergey Kravchenko (Northeastern, USA) - Anderson Localization and De-Localization in 2D
- Alexander Mirlin (KIT, Germany) - Anderson (de-)localization on random regular graphs and in many-body systems with power-law interaction

56 participants took active part in the lectures and discussions. New collaborations initiated as a result of this Workshop. As two examples we mention research on topological effects in doped graphene by Cheianov (Leiden) and Sharapov (Kyiv), and metal - insulator transition in strongly interacting two-dimensional systems by Kravchenko (Boston) and the organizers.

We appreciate very much extremely useful and helpful assistance by the local administrators Dr. Dominika Konikowska and Mrs. Sol Cho.

Topological States of Light and Beyond
Scientific coordinators: Andrey Miroshnichenko, Alexander Khanikaev, Hee Chul Park

The one-week topical Workshop on "Topological States of Light and Beyond" took place at IBS-PCS, preceding the following Advanced Study Group.

It attracted more than 30 participants from different international groups actively working on topological properties of various physical systems, including Australia, USA, Singapore, Japan, China, Russia, Switzerland, Germany, Netherland, and also local participants from a number of universities in Korea, as well as from IBS-PCS.

The key topics discussed during the workshop are the following:

- Topological photonic crystals
- Robustness against disorder
- Interacting and nonlinear topological systems
- Subwavelength topological edge states
- Quantum spin Hall effect of light

Among invited speakers were Alex Khanikaev, Yidong Chong, Konstantin Bliokh, Max Lein, Kun Woo Kim, Sung Bin Lee, Daniel Leykam, Alexander Moroz, Andrew Greentree, Alex Poddubny, Pilkyong Moon, Anton Souslov, Roman Susstrunk, Hyoung-In Lee, Jae Hoon Kim, Kwon Park, and Ivan Savenko.

During the workshop were given four introductory lecture, 20 invited and four contributing talks.

The lectures were presented by Andrey Miroshnichenko, Konstantin Bliokh, and Kwon Park. The first opening lecture was given by Andrey Miroshnichenko on general introduction to topological properties of physical systems. It followed by the overview of quantum spin Hall effect of light presented by Konstantin Bliokh. The lecture given by Kwon Park focused on topological phases of matter starting from quantum Hall effect to topological insulators and Weyl semimetals. The aim of those lectures were to introduce the concept of topological invariants and demonstration of their usages and application to various physical systems.

The invite talks covered a number of physical systems, which exhibit nontrivial topologically properties. It includes photonic crystals and lattices, spin-orbit interaction of light, photon blockade, topological insulators for light and sound, topological classification of wave equations, twisted bilayer graphene, nonlinear topological states of light, two level systems and geometrical phases, acoustic and mechanical metamaterials, anomalous phases and Weyl semimetals.

A number of talks sparked active discussions among the participants during the lunch and coffee breaks. The overall atmosphere was quite vivid and based on the general comments all the participants enjoyed it very much and found it very useful. The well prepared organisation and open communication among the participants stimulated quite productive interaction, which is expected to bring a number of fruitful outcomes.

In particular, inspired by the overall success of the workshop, Andrey Miroshnichenko organized another meeting at the University of Sydney, Australia, on “Topological Photonics”, which will take place 9 November this year. Several of workshop participants, including Yidong Chong, Konstantin Bliokh, and Alexander Poddubny, are going to attend it, which should promote their fruitful collaboration, initiated during the workshop in Korea.

Focus Workshop: Topology in Matter
Scientific coordinator: Hee Chul Park

A Focus Workshop entitled “Topology in Matter” was held at a PCS center seminar room from 25th - 27th November 2015 with ten invited speakers and contributing members. The speakers were invited to achieve the aim of gathering together the various young Korean scientists studying topological properties of matter, as our center provides scientific opportunities to students and young scientists as potential researchers. The demand for research on this issue has been revealed through both young and mature scientists recently concentrating on the topics with robust cooperation, as these are incredibly interesting issues containing prolific theoretical features.

Topologically nontrivial phases host new phenomena in matter such as topological surface states, topological superconductors, Weyl semi-metals, and AQHE, among others. In many cases, they are characterized by specific symmetries, and these topological properties are related to fundamental features in basic science. For instance, bulk-boundary correspondence, which is the interface between normal and abnormal phases, presents topologically protected states due to the change of the axionic field related to the symmetries. Relating to fundamental physics, a variety of exotic phenomena theoretically converge—this workshop focused on new exotic phenomena in various materials arising from topologically nontrivial phases, a milestone in new research and development. Speakers and participants enjoyed an interactive workshop with lively discussions between pioneers actively working in this field.

The workshop commenced with an opening address by Prof. Sergej Flach, Director of PCS-IBS, and concluded with closing remarks by Dr. Suk Bum Chung, a Young Scientist in CCES-IBS. Prof. Han Woong Yeom, Director of CALDES-IBS, gave us a unique experimental talk about a new topological class in 1D. The other main topics consisted of topological band theory, topological phase transitions, quantum criticality, vortex dynamics, Weyl semimetals, topological phases in He-3, and topological magnetoelectric effects, with details as follows.

- Han WoongYeom (CALDES IBS, Pohang) - Chiral edge state of 1D Z4 topological insulator
- Suk Bum Chung (CCES IBS, Seoul) - Topological Phases and Majorana fermions in He3 superfluid
- Hosub Jin (UNIST, Ulsan) - s-orbital Dirac fermions and topological electronics at oxide heterostructures
- Eun-Gook Moon (KAIST, Daejeon) - Topological Phase Transitions in Line-nodal Superconductors
- Pilkyung Moon (NYU Shanghai) - Fractal energy spectrum and quantum Hall effect in graphene superlattices
- Myoung Joon Han (KAIST, Daejeon) - First-principles study of large spin-orbit coupling transition-metal compounds: electronic structure and new possibilities
- Kun Woo Kim (KIAS, Seoul) - Weyl semimetal Fermi arc and its characterization in bulk
- Woo Ram Lee (KIAS, Seoul) - Fundamental connection between band topology and the winding number of the Wannier-Stark Ladder
- Yea-Lee Lee (SNU, Seoul) - Axion electrodynamics description of magnetic ordering on edges of topological insulators
- Gil Young Cho (KAIST, Daejeon) - Entanglement spectrum, symmetry-protected topological phases, and boundary conformal field theory.

The primary subject of the topological aspects of various materials, from graphene physics to He3 superfluid, was met with the strong cooperation and fruitful discussion that we had expected. This workshop, as a valuable opportunity for scientific exchange, also enabled PCS to build good relationships with KAIST, KIAS, Postech, SNU, and other IBS centers.

Nanomechanical systems: From New Materials to New Applications
Scientific coordinators: Kang-Hun Ahn, Andrew Cleland, Sergej Flach, Mikhail Kiselev

Extensive efforts exploring different materials and methods to study NEMS structures supported the advent of very high quality factor mechanical resonators with frequencies ranging from the MHz band well into the GHz band of frequencies. This has allowed the development of nanomechanical resonators as time-keeping systems competitive with macroscale quartz crystals; as radiofrequency filters for the cellphone industry; and increasingly as systems with strong potential for fundamental experiments in quantum mechanics as well as applications to quantum information technology. Nanomechanical systems also are playing an increasingly important and central role as ultrasensitive detectors of mass, displacement, acceleration, force or spin.

The applications that have become possible include measurements of forces between individual biomolecules, forces originating in the magnetic resonant response of single electron and nuclear spins, and noise that arises from mass fluctuations involving single molecules. As a result, this area of research attracts a large number of researchers from around the world. By their nature, nanomechanical systems are interdisciplinary, since they can couple to electrical circuits or optical cavities and they have potential applications in sensing, telecommunications, biophysics, and photonics, topics which are studied not only in condensed matter but also in the applied physics.

The recent integration of techniques to trap and strongly focus electromagnetic fields together with nanomechanical degrees of freedom, through the integration of high quality factor optical and microwave cavities with a high quality factor mechanical degree of freedom, has created an entire subfield that is expanding very rapidly, termed cavity optomechanics. Structures in which a version of a Fabry-Perot optical cavity is fabricated in a way that one of the two Fabry-Perot mirrors is mechanically active, or cavities where the two mirrors are fixed but a low-loss dielectric membrane is placed in a high field region of the cavity, have generated a number of very interesting physics results, including mechanically-induced transparency, sideband cooling of the mechanical mode, sideband amplification of the mechanical motion, and other effects intimately tied to the nonlinear parametric response of these systems.

The use of cavity optomechanical systems for the control and readout of nanomechanical systems has progressed to where now quantum mechanical effects are beginning to be seen in mechanical systems, although the first demonstration of operating a mechanical system in the quantum ground state, and also quantum control of that system, was first done using a piezoelectrically-based approach rather than one based on optomechanics. The advent of cavity optomechanics has also provided points of contact between nanomechanics and areas such as atomic physics and nonlinear optics.

Nanomechanical systems fabricated from a variety of materials have been explored in the course of this development, including the use of single-crystal semiconductors such as silicon and gallium arsenide; insulating materials such as amorphous silicon dioxide, silicon nitride and aluminum nitride; and metals including aluminum and niobium. These materials display specific properties that are useful for different applications, including superconductivity at low temperatures for some metals; good optical properties, especially for the silicon-based materials; and strong piezoelectric response for materials such as aluminum nitride and gallium arsenide.

The geometric structures explored, initially restricted to cantilevered and doubly-clamped beams, now include metal dome resonators; whispering gallery resonators; resonators based on defects in phononic and photonic crystals; and bulk dilatational and edge mode structures. The designs have evolved to include designs to minimize radiative acoustic loss and maximize interactions between the mechanical motion and electrical or electromagnetic (optical) fields, as well as ones that allow integration of quantum systems to detect or control the mechanical motion, or alternatively to generate responses in the mechanical system indicative of the state of the quantum system.

Recent important progress in NEMS research was presented in the workshop. To name a few, quantum aspect of NEMS by Prof. A. Cleland, and mass spectroscopy using graphene NEMS attracted great attention by the participants. Prof. B. Altshuler in Columbia University, a world-leading researcher of mesoscopic physics, participated in this meeting and built up the strong collaboration between NEMS and mesocopics. Almost all Korean NEMS researchers joined this workshop, and they decided to have Korean NEMS meeting on regular basis.

3.1.4 External Cofunding of Workshops and Seminars

- *Nanomechanical systems: from new materials to new applications*
  Workshop: July 26 - 30, 2015 (29% of the budget)
- *International Workshop on Non-Linear Effects and Short-Time Dynamics in Novel Superconductors and Correlated Spin-Orbit Coupled Systems*
  Workshop: September 18 - 22, 2017 (20% of the estimated budget)

3.1.5 Advanced Study Group Reports

Anderson Localization in Topological Insulators
Convener: Victor Kagalovsky

The ASG consisted of three members:

- Convener: Victor Kagalovsky (Shamoon College of Engineering, Israel),
- Alexander Chudnovskiy (University of Hamburg, Germany),
- Igor Yurkevich (Aston University, UK),

who visited PCS IBS for the period from August 24 till September 22, 2016, and two visitors:

- Oleg Evtushenko (University of Erlangen, Germany) 29.08 - 17.09
- Feo Kusmartsev (Loughborough University,UK) 4.09 - 22.09

This Advanced Study Group has focused on theoretical investigations of strongly correlated low dimensional electron systems. The ASG activities included numerous discussions, including two visitors, development of advanced mathematical apparatus to attack various perturbations in Luttinger liquids, and study of a number of physical problems, which we briefly list below.

The first problem we have addressed is a metal-insulator transition in a two-dimensional system, which we have modelled as a sliding Luttinegr liquid. Our results show the existence of such transition driven either by interactions or disorder, and are summarized in a paper attached to this report.

Another interesting problem is a study of various inter-wire scatterings in two coupled Luttinger channels as well as in an array of Luttinger wires. As one of the results we have reproduced right-to right moving scattering problem studied by one of our visitors (Theory of a 2D Luttinger liquid, FV Kusmartsev, A Luther, A Nersesyan, D Parsons, JETP letters 55, 724 (1992)) and considered the robustness of the phase under different perturbations.

We have also studied the interplay of localized and conducting phases in the bulk and at the edges of a two-dimensional system. We have found the conducting bulk in the presence of insulating edges in a fermionic system, whereas the opposite case effectively corresponding to a topological insulator can be realized only in a bosonic system.

We have also applied our results to a one-, two-, and three-channel models describing edge states in topological insulators with one, two, and three Kramers doublets respectively and have found regions of stability on the phase diagram.

We believe that the results of ASG activity will result in more than one paper. We will continue our collaboration through the year and obviously will be very happy to repeat our visit to Daejeon.

Topological States of Light and Beyond
Convener: Andrey Miroshnichenko

The Advanced Study Group on "Topological States of Light and Beyond" was preceded by a one week topical workshop on the same subject with more than 30 participants. Overall, the Advanced Study Group (ASG) did quite well to complement the workshop, which enabled further discussion and the exchange of research ideas among the ASG attendees as well as between ASG attendees and the permanent staff of IBS-PCS.

After the workshop seven participants remain and form the core o the ASG, which actively collaborated during following three weeks. During each day of ASG there were numerous regular meetings and detailed discussions on revealing of topological aspects of various physical systems, starting from condensed matter, nanophotonics, and even classical mechanics. The members of ASG naturally formed several subgroups, which focused further on more specific topics. Below we provide the joint summary and the current status of research activity of all ASG members.

Topological states of matter and non-hermitian quantum mechanics

Konstantin Bliokh and Daniel Leykam investigated topological edge states in non- Hermitian wave systems. They found that such states are intimately related to the presence of spectral degeneracies, i.e., exceptional points in non-Hermitian systems. Considering simplest model Hamiltonians, they noticed that edge modes always connect pairs of exceptional points, somewhat resembling topological states at Fermi arcs between Weil points in Hermitian Weil semimetals. They suggested classification of topological states in non-Hermitian systems, which can be of three types: "Hermitian", "non-Hermitian", and "mixed". Two topological numbers completely describe all these modes. They now hope to find a model physical system involving periodic lattice of resonators with loss and gain, which would manifest all these topological features. In any case, their study reveals remarkable links between two very hot topics of modern physics: topological states of matter and non-Hermitian quantum mechanics.

Classification of topological systems

Inspired by the invited talked of Max Lein titled "Topological Classification of Certain Wave Equations" it sparked a lot of interest on how the Altland-Zirnbauer classification of topological insulators can be adapted to a certain class of classical and bosonic wave equations. During the ASG program, there was the opportunity to continue the in-depth discussion with various members. In particular Daniel Leykam and Kun Woo Kim closely collaborated with Max Lein on the role non-linear effects in topological photonic crystals and topological periodic waveguide arrays. With Roman Süsstrunk and Anton Souslov they discussed their recent results on topological phenomena in acoustic and mechanical systems, and their similarities to topological photonic crystals. In addition to this, there were numerous discussions with Alexander Moroz about the significance of dispersion, and there was important literature survey with many helpful references (including rather important mathematically rigorous works).

It also sparked very fruitful the exchange of ideas on topological states of matter between various ASG members, including Anton Souslov, Max Lein, Alexander Moroz, and Andrey Miroshnichenko. The discussions involved the exchange of ideas between the areas of topological mechanics and soft condensed matte,which are the field of expertise of several ASG members, and wave mechanics, especially optics, which is the area of expertise of the other visitors. For example, Max Lein and Anton Souslov have started a collaboration in applying some of the mathematical techniques that Max Lein studies in the context of optics to the context of the acoustics of flowing liquids and the mechanics of waves in elastic solids.

Visit if Michael Lawler

A particular event during ASG at IBS-PCS, which has created useful scientific links and was partially organised by ASG member Anton Souslov, was the excursion from IBS-PCS to the KAIST physics department to attend the seminar by Prof. Michael Lawler (Binghamton University/Cornell University) titled “Isostatic Magnetism” and the subsequent visit by Michael Lawler to IBS-PCS that has fostered discussions between him and Anton Souslov, Max Lein, and Dr. Alexei Andreanov (IBS-PCS). These discussions have led to the exchange of ideas on topological materials in different contexts, including magnetism, solid mechanics, physics of electrons, and optics. It is expected that they will lead to a broader, more interdisciplinary research outlook for the scientists involved in these discussions and to further collaborations through a continuous exchange of ideas between scientists working in areas with common research interest.

Topological properties of cylindrical waveguides

Dmitry Kuzmin and Hyong In Lee have discussed some topological peculiarities of two-dimensional cylindrical waves propagation. Theoretical description of graphene conductivity has been discussed as well. The possibility of realization of topological states for cylindrical plasmonic waves localized near graphene layer has been consider. In the nearest future they plan to make a detail theoretical description of two-dimensional plasmonic waves in grapevine layer and prove an effect of meteorological properties of graphene and surrounding medium on plasmonic topological properties.

Notion of Berry’s phase in classical mechanics and Fano resonances

Andrey Miroshnichenko actively discussed the relation of Berry?s phase in classical mechanics with Alexander Moroz. They found that it has direct analogy in harmonic oscillator model and known as Hannay angle. To explicitly derive the analytical expression they used the Hamiltonian formalism of a driven generalised harmonic oscillator and used canonical transformations to reduce the system to action-angle variables. In the adiabatic approximation the Hannay angle associated with the intrinsic geometrical properties of the system can written is a simple integral form. As a next step, they are going to generalise this approach to two coupled driven oscillator, which can be considered as a classical analog of the Fano resonance. They still continue their active collaboration even after the ASG.

In addition to this, Andrey Miroshnichenko, Alex Moroz and Ivan Savenko (IBS-PCS) initiated research on application of the physics of the Fano resonances in exciton- polariton condensates. It is expected that the results of this activity will be experimentally verified. They continue their regular discussions over the Skype.

Outcomes

Overall, it is expected that the outcomes of a numerous research activities during ASG will published in several scientific peer-reviewed publications in world leading journals, as well as delivered at international conferences. Several members continue their fruitful collaboration, initiated during ASG.

Nonergodicity in Quantum and Classical Many Body Systems

Conveners: Boris Altshuler, Sergej Flach

This ASG took place during May 9 - June 20 2016. The members actively discussed and worked on recent advances in the physics of nonergodic transport of many-body systems in all its quantum and classical facets. In particular potential regimes of nonergodic metallic phases were critically explored in the light of such further concepts as Kolmogorov-Arnold-Moser regime, Arnold web and diffusion, amongst others. We also explored its relation to topological properties of matter. Another strong focus was on dissipative quantum systems, in particular the collective dynamics in dissipative condensates. The following scientists participated in the ASG: Gil Young Cho (KAIST, South Korea), Sergey Denisov (Augsburg University, Germany), Lara Faoro (LPTHE CNRS, France), Rozario Fazio (ICTP, Italy), Shmuel Fishman (Technion Haifa, Israel), Lev Ioffe (Rutgers University, USA), Ki-Seok Kim (POSTECH, South Korea), Vladimir Kravtsov (ICTP, Italy), Eun-Gook Moon (KAIST, South Korea), Antonio Politi (University of Aberdeen, UK), Yuri Rubo (UNAM, Mexico), Heung-Sun Sim (KAIST, South Korea), Wei-min Wang (University of Paris-Sud, France), Vladimir Yudson (RAS Institute, Russia), Emil Yuzbashyan (Rutgers University, USA). the following topics were considered:

- Two-parameter scaling theory of the longitudinal magneto conductivity in a Weyl metal phase: Chiral anomaly, weak disorder, and finite temperature
- Energy transport between two integrable spin chains
- Ergodic transitions in hierarchical and many-body systems
- Entanglement in condensed matter: Towards finite temperature
- Spin bifurcations in exciton-polariton condensates
- Quantum Anomaly, Lieb-Schultz-Mattis Theorem, and Symmetry-Protected Topological Phases
- Spin impurities in topological insulators
- Between Localization and Ergodicity in Quantum Systems
- Out-of-time-order-correlators in solid state physics
- Non-ergodic phases in strongly disordered random regular graphs
- Statistical Description of Dynamical Systems in Mixed Phase Space: Chaotic and Regular
- Far from equilibrium phases of superfluid matter
- Metastable quasi-stationary states of open quantum systems
- Metastable (or quasi-stationary) states of open quantum systems
- Topological Phase Transitions in Line-nodal Superconductors

Many Body Localization, Nonergodicity, and All That
Conveners: Boris Altshuler, Sergej Flach

The Advanced Study Group *Many Body Localization, Nonergodicity, and All That* was the first event taking place on the premises of the PCS center during June 23 - July 31 2015. In fact the center moved into temporary offices a week before the the ASG started, and during this ASG we whitenessed the refurbishing of the PCS offices which we are currently occupying. During this activity we actively discussed and worked on recent advances in the physics of many-body localization in all its quantum and classical facets. In particular potential regimes of nonergodic metallic phases were critically explored in the light of such further concepts as Kolmogorov-Arnold-Moser regime, Fermi-Pasta-Ulam paradox, Arnold web and diffusion, amongst others. members of the ASG included world class specialists

Igor Aleiner (Columbia U), Richard Berkovits (Bar Ilan U), Sergey Denisov (Augsburg U), Lara Faoro (CNRS), Lev Ioffe (Rutgers), Antonio Politi (Aberdeen U), Emil Yuzhbashyan (Rutgers), and young participants Joshua Bodyfelt (Massey U) and Xiaoquan Yu (Otago U). Intense open discussions together with 2-3 talks per week set the stage of this very fruitful ASG. Richard Berkovits delivered a tutorial on DMRG methods, and Emil Yuzhbashyan gave a blackboard lecture series on *Generalized Gibbs Ensemble DeMystified*. Several research studies were initiated during that event. In particular we worked on the following topics:

- Entanglement Properties and Quantum Phase Transitions in Many Body Disordered One Dimensional Systems
- Anderson Localization and Quasiperiodics within Flatband Lattices
- Aubry Andre model, Approximated and Exact Metal-Insulator Transition
- The internal structure of a vortex in a two-dimensional superfluid with long healing length
- Phase diagram of one-dimensional Josephson junction chain: non-ergodicity and many body localization
- Quantum Levy flights
- Non-Gibbs phases, self-trapping and nonlinear wave spreading in disordered DNLS chains
- Anomalous perturbation spreading in two-dimensional nonlinear lattices
- Microscopic theory of flux noise

3.1.6 Lectures and seminar presentations at PCS

Date	Title	Speaker
20.10.2016	An extended DNLS model as a wave diode	M.A. Wasay, Pakistan
19.10.2016	Recent progress at Quantum Computing and Devices Laboratories	M. Möttönen, Finland
11.10.2016	Theoretical description of bias-controlled polariton devices	D. Karpov, Finland
29.09.2016	The multifaceted role of quenched disorder in condensed matter systems	R. Narayanan, India
27.09.2016	Attosecond Physics gets Nano	M. Ciappina, Czech Rep.
20.09.2016	The structure of deterministic mass, surface and multi-phase fractals from small-angle scattering data	A. Cherny, Russia
24.08.2016	Pairing Dynamics of quenched Superfluid Fermi gases	S. Yoon, Korea
12.08.2016	New Approach to Material and Tissue Aging	J. Schreiber, Germany
08.08.2016	Large-scale approach to complex biological systems	P.-J. Kim, Korea
04.08.2016	Acousto-exitonic effects in 2D dipolar exciton gas	V. Kovalev, Russia

03.08.2016	Solitonic vortex in a compressible superfluid	L. Toikka, New Zealand
02.08.2016	Flat band and dipolar discrete optics	R. Vicencio, Chile
20.06.2016	Nonlinear dynamics of exciton-polariton open-dissipative quantum fluid	G. Li, Australia
17.06.2016	Universal Many-Body Interference beyond Mean-Field Theory in Fock Space	T. Engl, New Zealand
17.06.2016	Topological Phase Transitions in Line-nodal Superconductors	E.-G. Moon, Korea
16.06.2016	Time quasi-periodic solutions to the nonlinear Klein-Gordon equations on higher dimensional torus	W.-M. Wang, France
15.06.2016	Metastable (or quasi-stationary) states of open quantum systems	S. Denisov, Germany
14.06.2016	Far from equilibrium phases of superfluid matter	E. Yuzbashyan, USA
13.06.2016	Statistical Description of Dynamical Systems in Mixed Phase Space: Chaotic and Regular	S. Fishman, Israel
10.06.2016	Fractional lattice charge transport	R. Khomeriki, Georgia
09.06.2016	Non-ergodic phases in strongly disordered random regular graphs	L. Ioffe, USA
08.06.2016	Coupled Transport in One-dimensional Systems	A. Politi, UK
07.06.2016	Out-of-time-order-correlators in solid state physics	L. Faoro, France
02.06.2016	Reconciling Tunneling Spectroscopy and Photoemission Spectroscopy in Cuprate and Pnictide Superconductors	J. Hong, Korea
31.05.2016	Between Localization and Ergodicity in Quantum Systems	B. Altshuler, USA
26.05.2016	Spin impurities in topological insulators	V. Yudson, Russia
24.05.2016	Quantum Anomaly, Lieb-Schultz-Mattis Theorem, and Symmetry-Protected Topological Phases	G.Y. Cho, Korea
23.05.2016	Spin bifurcations in exciton-polariton condensates	Y. Rubo, Mexico
19.05.2016	Entanglement in condensed matter: Towards finite temperature	H.-S. Sim, Korea
18.05.2016	Ergodic transitions in hierarchical and many-body systems	V. Kravtsov, Italy
17.05.2016	Energy transport between two integrable spin chains	R. Fazio, Italy

16.05.2016	Dynamics of quantum correlations in many-body systems	U. Mishra, Korea
12.05.2016	Effects of disorder on vortex dynamics in Bose-Einstein Condensates	M. Thudiyangal, India
11.05.2016	Two-parameter scaling theory of the longitudinal magneto conductivity in a Weyl metal phase: Chiral anomaly, weak disorder, and finite temperature	K.-S. Kim, Korea
10.05.2016	Electronic correlations and excitons in optically active polymers	N. Kirova, France
09.05.2016	Modeling of nonlinear and non-stationary multi vortex behavior of CDW in restricted geometries of mesa junctions	N. Kirova, France
04.05.2016	Observed hidden magnetic order as pseudogap and superconductivity pairs and set of underdone metal insulator-crossover phenomena as keystone of physics of cuprates	B. Abdullaev, Uzbekistan
04.05.2016	Dynamical phase transitions in electronic systems induced by ultra-fast optical pumping	S. Brazovskii, France
03.05.2016	Solitons in correlated electronic systems: at one dimension and beyond	S. Brazovskii, France
02.05.2016	Low dimensional electronic systems: firework of symmetry broken ground states and their collective effects	S. Brazovskii, France
29.04.2016	Critical Phenomena in Disordered Magnets: Lecture II	E. Kogan, Israel
28.04.2016	Quantum Fluctuation Theorems and Power Measurements	G. Watanabe, China
27.04.2016	Critical Phenomena in Disordered Magnets: Lecture I	E. Kogan, Israel
26.04.2016	Hamilton-Jacobi trajectories of comets Kohoutek and ISON: A novel approach to celestial dynamics	M.H. Lee, USA
26.04.2016	Wave-number dependent dynamics for a harmonic oscillator	I. Sawada, Japan
25.04.2016	Elementary Chemical Reaction Theory revisited: Application to Biochemistry	S. Aubry, France
19.04.2016	Collective States in Optical Cavities	V. Fleurov, Israel
19.04.2016	Single Photons from Dissipations in Coupled Cavities	H. Flayac, France
18.04.2016	Long-range Coulomb interaction in nodal-ring semimetals	Y. Huh, Canada

15.04.2016	Fluids Close to Two-dimensionality: Statics and Dynamics	R. Schilling, Germany
14.04.2016	Converting the Schelling's segregation model into Markov chains	M. Vert, France
12.04.2016	Phase transitions in disordered magnets	E. Kogan, Israel
08.04.2016	Electric-field-induced nonequilibrium physics in condensed matter systems	K. Park, Korea
07.04.2016	Some Predictions Arising from a Novel Dynamic Theory for Smectic A Liquid Crystals	B. Snow, UK
06.04.2016	Adaptive Truncation of the Hilbert Space in the Impurity Solver for the Dynamical Mean-field Theory	A. Go, USA
23.03.2016	Two-Component Bose-Einstein Condensates in Ring Cavities	F. Mivehvar, Canada
22.03.2016	Information Thermodynamics of Small Systems	A. Kutvonen, Finland
22.03.2016	Local Heating and Cooling Criterion in Nanoscale Systems	E. Amanatidis, Taiwan
21.03.2016	The Promise of Big Data and Machine Learning for Physics and Chemistry	K. Kladko, USA
19.02.2016	Fluctuation theorem and phase transitions: emergent universal scaling of nonequilibrium processes in critical systems	G. Watanabe, Korea
18.02.2016	Introduction to Heterogeneous HPC	H. Ryu, Korea
18.02.2016	A computational approach to novel materials under pressure	D.Y. Kim, China
17.02.2016	Cooperative effects in quantum transport: shielding and localization	G.L. Celardo, Italy
12.02.2016	Cooperative effects in quantum transport: Cooperative Shielding	G.L. Celardo, Italy
11.02.2016	Quasiparticle interference in heavy fermion superconductors	A. Akbari, Korea
05.02.2016	Report on diamond chain in the presence of magnetic field	H. Hatami, Korea
02.02.2016	Two bosons system with delta-function interaction and kicked driven potential	P. Qin, Korea
01.02.2016	Quasiperiodic driving of Anderson localized waves in one dimension	H. Hatami, Korea
28.01.2016	Generalization of one dimensional flatband lattice models	W. Maimaiti, Korea
27.01.2016	Application of Deep Learning Algorithm to Systems with Chaos	N. Khotkevych, Kora

18.01.2016	Relativistic and Topological Dynamics of Topological Materials	M.-S. Choi, Korea
21.12.2015	Low Dimensional Nanostructure Based NEMS: Fundamental Studies and Applications	S.W. Lee, Korea
10.12.2015	Abandoned Symmetry	V. Yurovsky, Israel
30.11.2015	Lecture on Deep Learning II	K.-H. Ahn, Korea
24.11.2015	Lattice sphere packing: the importance of being perfect	A. Andreanov, Korea
23.11.2015	Revealing single-trap fragmented condensates as "photonic" Schrodinger cat states	U. Fischer, Korea
23.11.2015	New phenomena of quantum chaos in optical microcavities	J.-W. Ryu, Korea
02.11.2015	Lecture on Deep Learning I	K.-H. Ahn, Korea
19.10.2015	2D and 3D light bullets in carbon nanostructures: Interaction of electromagnetic pulses with an electron inhomogeneity in an array of carbon nanotubes	E. Fedorov, Russia
16.10.2015	Wavefunctions for large electron numbers	P. Fulde, Germany
16.10.2015	Interference of a single charged particle produced from two independent sources	K. Kang, Korea
13.10.2015	Traveling Intrinsic Localized Modes in a Driven-Damped Nonlinear Lattice	M. Sato, Japan
12.10.2015	A closer look to scanning tunneling microscopy: beginning, flourishing and prospects	N. Khotkevych, Ukraine
08.10.2015	Localized chaotic patterns in weakly dissipative magnetic systems	D. Laroze, UK
07.10.2015	Coherent quantum transport of exciton polaritons in mesostructures	I. Savenko, Finland
30.09.2015	Quantum Quench of Cold Fermi Gases	S. Yoon, Korea
11.09.2015	Cyclotron motions in exotic semi-metals	J.W. Rhim, Korea
10.09.2015	Stabilization of solitons under competing nonlinearities by external potentials	K. Zegadlo, Poland
09.09.2015	Stable two-dimensional semi-vortex solitons in spin-orbit-coupled self-attractive Bose-Einstein condensates in free space	B. Malomed, Israel
08.09.2015	Weak ergodicity breaking: from single molecules in the live cell to blinking quantum dots	E. Barkai, Israel
07.09.2015	Long Range Interactions in Physical and Biological Complex Systems	T. Bountis, Greece

04.09.2015	Transition fronts and oscillatory tails in nonlinear lattices	O. Gendelman, Israel
03.09.2015	Effective rate constant for nanostructured heterogeneous catalysis	L. Rajabi, New Zealand
20.08.2015	Heat dissipation and its relation to molecular orbital energies in single-molecule junctions	J. Vahedi, Iran
17.08.2015	Analogue Hawking radiation in an Nonlinear Optical System	V. Fleurov, Israel
20.07.2015	Origami rules for the construction of localized eigenstates of the Hubbard model in decorated lattices	R. Guimaraes, Portugal
16.07.2015	Quantum Band-Gap Transmission	R. Khomeriki, Georgia
15.07.2015	Generalized Gibbs ensemble DeMystified 3	E. Yuzbashyan, USA
15.07.2015	Zeno dynamics and Cooperative Shielding from long range interaction in disordered models for quantum transport	G.L. Celardo, Italy
14.07.2015	Generalized Gibbs ensemble DeMystified 2	E. Yuzbashyan, USA
14.07.2015	Generalized Gibbs ensemble DeMystified 1	E. Yuzbashyan, USA
14.07.2015	Coupled transport in chains of oscillators	A. Politi, UK
10.07.2015	Charged dendrimers under the action of DC and AC electric fields: Shape distortions, master curves, breathing characteristics, polarizations and ion distributions	A.K. Das, Korea
10.07.2015	Microscopic theory of flux noise and open questions	L. Faoro, France
09.07.2015	Anomalous perturbation spreading in two-dimensional nonlinear lattices	S. Denisov, Germany
09.07.2015	Non-Gibbs phases, self-trapping and nonlinear wave spreading in disordered DNLS chains	X. Yu, New Zealand
08.07.2015	Quantum Levy flights	B. Altshuler, USA
07.07.2015	Phase diagram of one-dimensional Josephson junction chain: non-ergodicity and many body localization	L. Ioffe, USA
07.07.2015	The internal structure of a vortex in a two-dimensional superfluid with long healing length	I. Aleiner, USA
06.07.2015	Shaping the wavepackets of relativistic particles: altering their lifetime and radiation	I. Kaminer, USA
03.07.2015	Quadrupolar Kondo Effect in Iron-based Superconductor Sr2VO3FeAs	H.-J. Lee, Korea
02.07.2015	Aubry Andre model, Approximated and Exact Metal-Insulator Transition	C. Danieli, New Zealand

01.07.2015	Anderson Localization and Quasiperiodics within Flatband Lattices	J. Bodyfelt, New Zealand
30.06.2015	Entanglement Properties and Quantum Phase Transitions in Many Body Disordered One Dimensional Systems	R. Berkovits, Israel
29.06.2015	Non-linear phenomena in superfluid Fermi gases in an optical lattice - swallowtails and period doubling	G. Watanabe, Korea
26.06.2015	Tutorial on Entanglement and Density Matrix Renormalization Group methods	R. Berkovits, Israel
10.06.2015	Dynamical Anderson transition in one-dimensional periodically kicked incommensurate lattices	P. Qin, Korea
09.06.2015	Equilibrium and Non-equilibrium Kondo Phenomena	J. Hong, Korea
03.06.2015	Plasmon assisted optical properties of linear and nonlinear nano-systems	A. Ramachandran, India
02.06.2015	Boson Sampling for Molecular Vibronic Spectra	J. Huh, USA

3.2 Appointments and Awards

With less than two years since the foundation of PCS, *Prof. 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*).

3.3 Teaching and Education

Our center currently hosts two PhD students, and two more candidates are expected to enroll as PhD students in the near future. All are part of the IBS School, a Graduate School with enrollment at the *University of Science and Technology* (UST). To ensure highest standards of PhD training for all IBS School students, we will offer lecture series on a regular basis starting with 2017. Course topics will be closely related with the research topics of PCS. Currently *Prof. Sergej Flach* is a full-time faculty member of UST. Three more PCS team leaders are in the process of being appointed as UST faculty members.

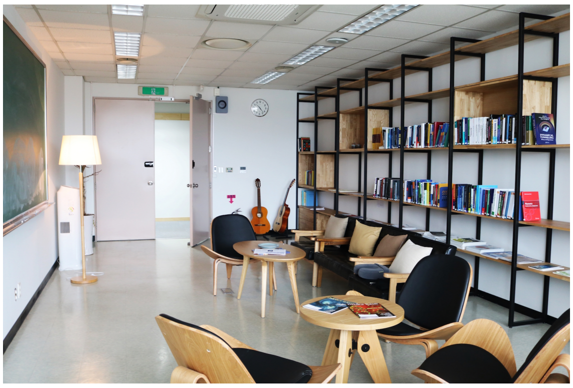
3.4 Equipment and Premises

3.4.1 Computing Facilities

Computational facilities are highly important for successful research in the field of theoretical physics of complex systems. For general computational tasks we are offering a Linux based cluster with currently 32 nodes, 2 CPUs per node, 12 cores per CPU, a total of 768 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. We further installed, or are installing, several high performance desktops (nodes) 512 GB memory each for high performance computations which require large memory capacity, and also for test running 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 IBS Center for Theoretical Physics of Complex Systems (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?s comfortable and modern facilities with journal boards, computers, blackboards, reading corners, and work desks. International e-journals are also available, following IBS and KAIST guidelines. Our library stock is soon to consist of about 200 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 by way of the PCS homepage, where users will soon be able to register. Currently we are arranging the means for users to access e-documents and e-books on the library homepage via their computers with identified IP addresses.

3.5 Center Advisory Board

To support PCS directors in their effort to maintain the research excellence of the Center and promote its constant growth, the PCS Advisory Board has been established. Reviewing the scientific reports prepared by 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 Advisory Board meeting will take place in December 2016.

PCS Advisory Board consists currently of the following members:

Name	**Affiliation**
Boris Altshuler	Columbia University, USA
Yunkyu Bang	Chonnam National University, Korea
David Campbell	Boston University, USA
Yong-Hoon Cho	KAIST, 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 Haifa, Israel

3.6 Members of the PCS

(as of Nov. 2016)

Position	**No.**
Director	1
Research Fellows	17
- Junior Research Team Leaders	3
- Deputy Team Leaders	1
- Visiting Research Fellows	1
Researchers	2
Ph.D. Students	3
- Visiting Ph.D. Students	1
Administrative staff	4
- Visitors Program	1

D: Director
T: Tenure-track
RF: Research Fellow
R: Researcher / Ph.D. Student

Name	**Period**	**Country**	**R(F)**	**Research team**
Ilias Amanatidis	since 09/16	Greece	RF	Quantum Many-Body Interactions and Transport
Alexei Andreanov	since 09/15	Russia	RF	Complex Condensed Matter Systems
Hwa Sung Cheon	since 03/15	Korea	RF	IT Manager
Sergej Flach	since 12/14	Germany	D	Complex Condensed Matter Systems
Ara Go	since 11/16	Korea	T	Strongly Correlated Electronic Systems
Hani Hatami	06/15 - 07/16	Iran	RF	Complex Condensed Matter Systems
Jongbae Hong	since 06/15	Korea	RF	Complex Condensed Matter Systems
Yagmur Kati	since 04/16	Turkey	R	Complex Condensed Matter Systems
Natalia Khotkevych	01/16 - 03/16	Ukraine	RF	Complex Condensed Matter Systems
Dominika Konikowska	since 04/16	Poland	RF	Visitors Program Coordinator
Minyoung Lee	since 06/16	Korea	R	IT Staff
Wulayimu Maimaiti	since 10/15	China	R	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Nojoon Myoung	since 04/16	Korea	RF	Quantum Many-Body Interactions and Transport
Hee Chul Park	since 05/15	Korea	T	Quantum Many-Body Interactions and Transport
Pinquan Qin	since 05/15	China	RF	Complex Condensed Matter Systems & Quantum Many-Body Interactions and Transport
Ajith Ramachandran	since 05/16	India	RF	Complex Condensed Matter Systems
Jung-Wan Ryu	since 10/16	Korea	RF	Complex Condensed Matter Systems
Ivan Savenko	since 02/16	Russia	T	Light-Matter Interaction in Nanostructures

Meng Sun	since 02/2016	China	R	Light-Matter Interaction in Nanostructures
Ihor Vakulchyk	since 10/16	Ukraine	R	Complex Condensed Matter Systems
Mew-Bing Wan	09/15 - 04/16	Malaysia	RF	Visitors Program Coordinator
Gentaro Watanabe	05/15 - 02/16	Japan	RF	Complex Condensed Matter Systems
Sukjin Yoon	since 10/16	Korea	RF	Light-Matter Interaction in Nanostructures

Chapter 4

Publications

2016

Alexei Andreanov, Antonello Scardicchio, Salvatore Torquato, *Extreme lattices: symmetries and decorrelations*, J. Stat. Mech. (2016) 113301 [arXiv:1309.1301].

J. Vahedi, M. Shabani Arbousara, S. Mahdavifar, *Zero-Temperature Study of a Tetrameric Spin-1/2 Chain in a Transverse Magnetic Field*, J. Low. Temp. Phys. 185 (2016) 1 [arXiv:1608.02145].

G.L. Celardo, R. Kaiser, and F. Borgonovi, *Shielding and localization in presence of long range hopping*, Phys. Rev. B 94 (2016) 144206 [arXiv:1604.07868].

Raka Dasgupta, B. Prasanna Venkatesh, Gentaro Watanabe, *Attraction-induced dynamical stability of a Bose-Einstein Condensate in a nonlinear lattice*, Phys. Rev. A 93 (2016) 063618 [arXiv:1603.07486].

G. Gligorić, A. Maluckov, Lj. Hadžievski, Sergej Flach, and Boris A. Malomed, *Nonlinear localized flat-band modes with spin-orbit coupling*, Phys. Rev. B 94 (2016) 144302 [arXiv:1609.09640].

H. Hatami, C. Danieli, J.D. Bodyfelt, and S. Flach, *Quasiperiodic driving of Anderson localized waves in one dimension*, Phys. Rev. E 93 (2016) 062205 [arXiv: 1602.02476].

Danh-Tai Hoang, B. Prasanna Venkatesh, Seungju Han, Junghyo Jo, Gentaro Watanabe, and Mahn-Soo Choi, *Scaling Law for Irreversible Entropy Production in Critical Systems*, Scientific Reports 6 (2016) 27603 [arXiv:1508.02444].

Jongbae Hong, D.S.L. Abergel, *A universal explanation of tunneling conductance in exotic superconductors*, Scientific Reports 6 (2016) 31352 [arXiv:1411.5532].

D.V. Karpov and I.G. Savenko, *Operation of a semiconductor microcavity under electric excitation*, Applied Physics Letters 109 (2016) 061110 [arXiv:1605.08447].

Ramaz Khomeriki and Sergej Flach, *Landau-Zener Bloch Oscillations with Perturbed Flat Bands*, Phys. Rev. Lett. 116 (2016) 245301 [arXiv:1602.08691].

Yushin Kim, Soo-Young Lee, Jung-Wan Ryu, Inbo Kim, Jae-Hyung Han, Heung-Sik Tae, Muhan Choi, and Bumki Min, *Designing whispering gallery modes via transformation optics*, Nature Photonics 10 (2016) 647.

E. Kogan, *Lift force due to odd Hall viscosity*, Phys. Rev. E 94 (2016) 043111 [arXiv:1606.05082].

Yannis Kominis, Tassos Bountis, Sergej Flach, *The Asymmetric Active Coupler: Stable Nonlinear Supermodes and Directed Transport*, Scientific Reports 6 (2016) 33699 [arXiv:1606.03310].

Nojoon Myoung, Hee Chul Park, and Seung Joo Lee, *Gate-Tunable Spin Transport and Giant Electroresistance in Ferromagnetic Graphene Vertical Heterostructures*, Scientific Reports 6 (2016) 25253 [arXiv:1510.07858].

Javad Vahedi, Fattaneh Barimani, *Spin and charge thermopower effects in the ferromagnetic graphene junction*, Journal of Applied Physics 120 (2016) 084303 [arXiv:1608.02142].

Gentaro Watanabe, B. Prasanna Venkatesh, and Raka Dasgupta, *Nonlinear Phenomena of Ultracold Atomic Gases in Optical Lattices: Emergence of Novel Features in Extended States*, Entropy, 18 118 (2016) [Review article in a special issue on "Non-Linear Lattice"].

Sungjong Woo, Hee Chul Park, and Young-Woo Son, *Poisson's ratio in layered two-dimensional crystals*, Phys. Rev. B 93, (2016) 075420 [arXiv:1507.07324].

Sukjin Yoon, Franco Dalfovo, Takashi Nakatsukasa, and Gentaro Watanabe, *Multiple period states of the superfluid Fermi gas in an optical lattice*, New Journal of Physics 18 (2016) 023011 [arXiv:1503.07976].

2015

Carlo Danieli, Joshua D. Bodyfelt and Sergej Flach, *Flat-band engineering of mobility edges*, Phys. Rev. B 91 (2015) 235134 [arXiv:1502.06690].

C. Danieli, K. Rayanov, B. Pavlov, G. Martin, S.Flach, *Approximating Metal-Insulator Transitions*, Int. J. Mod. Phys. B 29 (2015) 1550036 [arXiv:1405.1694].

Sergej Flach, *Spreading, Nonergodicity, and Selftrapping: A Puzzle of Interacting Disordered Lattice Waves*, Springer International Publishing Switzerland 2015, Mustapha Tlidi and Marcel G. Clerc (eds.), Nonlinear Dynamics: Materials, Theory and Experiments, Springer Proceedings in Physics 173.

Sergej Flach, *Nonlinear Lattice Waves in Random Potentials*, Springer International Publishing Switzerland 2015, C. Besse, J.-C. Garreau (eds.), Nonlinear Optical and Atomic Systems, Lecture Notes in Mathematics 2146.

Sergej Flach and Joshua D. Bodyfelt, *Brennpunkt: Eingesperrt - nicht hinter, sondern auf dem Gitter* Physik Journal 14 (2015) 24-25.

D.O. Krimer, S. Flach, *Interaction-induced connectivity of disordered two-particle states*, Phys. Rev. B 91 (2015) 100201(R) [arXiv:1407.0680].

Yea-Lee Lee, Hee Chul Park, Jisoon Ihm, and Young-Woo Son, *Manifestation of axion electrodynamics through magnetic ordering on edges of a topological insulator*, PNAS 112 (2015) 11514 [arXiv:1411.3831].

K. Rayanov, B.L. Altshuler, Y.G. Rubo, S. Flach, *Frequency Combs with Weakly Lasing Exciton-Polariton Condensates*, Phys. Rev. Lett. 114 (2015) 193901 [arXiv:1501.02053].

B. Prasanna Venkatesh, Gentaro Watanabe, and Peter Talkner, *Quantum fluctuation theorems and power measurements*, New J. Phys. 17 (2015) 075018 [Focus Issue on Quantum Thermodynamics] [arXiv:1503.03228].

Preprints

C. Danieli, D.K. Campbell, S. Flach, *Intermittent FPU dynamics at equilibrium*, arXiv:1611.00434 [nlin.CD].

M. Boev, V.M. Kovalev, I.G. Savenko, *Magnetoplasmon Fano resonance in Bose-Fermi mixtures*, arXiv:1610.07316 [cond-mat.mes-hall].

Sergej Flach and Ramaz Khomeriki, *Fractional lattice charge transport*, arXiv:1606.03703

[cond-mat.dis-nn].

E. Kogan and M. Kaveh, *Critical behaviour of anisotropic magnets with quenched disorder: replica symmetry breaking studied by operator product expansion*, arXiv: 1602.06789 [cond-mat.stat-mech].

E. Kogan and M. Kaveh, *Replica symmetry breaking for anisotropic magnetics with quenched disorder*, arXiv: 1603.06383 [cond-mat.stat-mech].

V.M. Kovalev, I.G. Savenko, *Paramagnetic Resonance in Spin-Polarized Disordered Bose Condensates* arXiv:1609.06411 [cond-mat.mes-hall].

Daniel Leykam, Joshua D. Bodyfelt, Anton S. Desyatnikov, and Sergej Flach, *Localization of weakly disordered flat band states*, arXiv:1601.03784 [cond-mat.dis-nn].

Wulayimu Maimaiti, Alexei Andreanov, Hee Chul Park, Oleg Gendelman, Sergej Flach, *Compact localized states and flatband generators in one dimension*, arXiv:1610.02970 [cond-mat.mes-hall].

Pinquan Qin, Alexei Andreanov, Hee Chul Park, and Sergej Flach, *Interacting ultracold atomic kicked rotors: dynamical localization?*, arXiv:1606.08964 [cond-mat.quant-gas].

M. Sun, I.G. Savenko, H. Flayac, T.C.H. Liew, *Nontrivial ground state engineering in exciton-photon lattices*, arXiv:1610.05473 [cond-mat.mes-hall].

Sukjin Yoon and Gentaro Watanabe, *Pairing Dynamics of Polar States in a Quenched p-wave Superfluid Fermi Gas*, arXiv:1512.09058 [cond-mat.quant-gas].