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要旨集

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Solvent effect of normal alkane on blue phase

Soft Matter Physics Group Hitoshi TAKAO

Abstract We investigated the solvent effect caused by mixing normal alkane molecules with cholesteric blue phase (BP). As the result, we found that BP was stabilized under wide temperature range by the addition of alkane molecules. we revealed that alkane molecules are uniformly distributed in BP and weaken chiral interaction.

(Cholesteric) Blue Phase (BP), which appears in narrow temperature region, about 1℃, between cholesteric (Ch) and isotropic (I) phase, has characteristic molecular arrangements. Since strong chiral interaction induces the short pitch twist of the nematic director, and the cylinder arrangements twisted to radial direction. This is so called "double twist cylinder (DTC)", which are embedded in cubic lattice of a few hundred nm. Since DTCs cannot fill up the space continuously, disclination lines should be created and intercalated among DTC in BPs. Recently, many researchers achieved to expand BP temperature region by addition of polymer and nano-sized molecules etc… to change Frank elasticity and free energy density of system [1,2,3]. However, there are few reports about BP stabilization by mixing simple low molecular organic solvent with BP.

In this study, we investigated solvent effect diluted by normal alkane. As the result, we found that BP was stabilized under wide temperature range by the addition of alkane molecules (Fig.1). To clarify mechanism of this effect, we measured the dependence of helical pitch of both BP and Ch phase on solvent concentration. As the result, it was confirmed that helical pitch equally increases in both phases (Fig.2). Therefore, it is found that solvent molecules are not localize in the core of defects and uniformly disperse entirely. Furthermore, we demonstrated alkane molecules weaken chiral interaction of LC molecules.

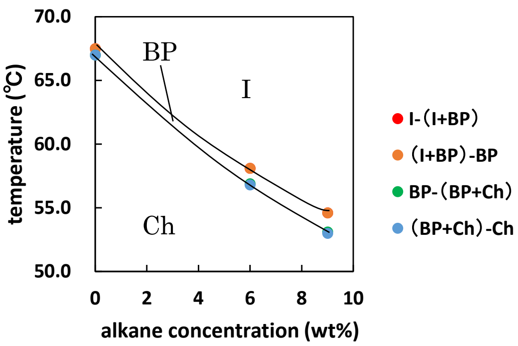

Fig.1:Temperature-concentration phase diagram for BP-alkane miscible system..

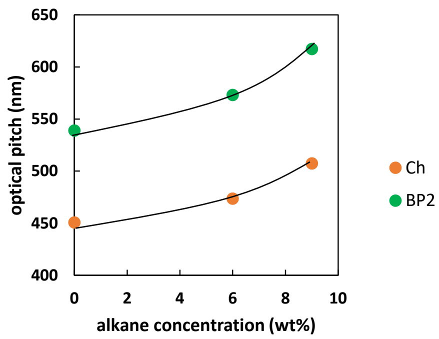

Fig.2: The dependence of optical pitch of BP and Ch on alkane concentration.

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Development of a programmable quantum system using single Ytterbium atoms trapped in an optical tweezer array

Quantum Optics Group Daichi Okuno

Abstract We report progress towards the realization of high-fidelity quantum gate operations using Ytterbium atoms. We have succeeded in two key experiments of trapping and imaging of single atoms and the excitation to Rydberg states following the excitation to the $^3P_2$ metastable state.

Recently single atoms trapped by a reconfigurable array of micro-optical traps have been attracting attentions. In addition, controlled excitation to Rydberg states — highly excited states with an outermost electron(s) occupying the orbit with a large principal quantum number — will produce interactions between atoms in distant sites (typically few μm), and it enables bottom-up construction of a quantum system for the study of quantum physics, especially neutral atom quantum computation [1]. In this study, we focus on Ytterbium (Yb) atoms which possesses many advantageous properties stemming from two valence electrons: the existence of optical transitions between Rydberg states ((6s)(*nl*) → (6p)(*nl*)), long-lived metastable excited states, and Zeeman sublevels of nuclear spin in the ground state of fermionic isotopes ^{171}Yb or ^{173}Yb which are less sensitive to magnetic fields [2]. Here we report two key experiments towards the construction of a scalable quantum computer which utilizes above mentioned nature of Yb atoms.

First, we show the result of trapping and imaging of single Ytterbium atoms. We generated two-dimensional array of tightly focused light through an objective lens (NA=0.6), by applying multi-tone RF to two orthogonal Acousto-Optic Deflectors (AODs) which deflect the laser with desired angles in two dimensions. We used 532nm laser for the trap and this creates quite a deep potential for the ground state atoms, typically ~1mK. We confirmed that we successfully achieved nearly diffraction-limited beam waist of 1μm by measuring the trap frequency of the atoms in the potential. As shown in Fig. 1, we have succeeded in getting images of single atoms by detecting the fluorescence and observed a stochastic behavior of the loading to the trap, namely each site is filled or empty with 50% probability, due to the pairwise loss assisted by near-resonant red detuned light for the purpose of excluding multiple atoms in one trap site [3].

Second, we succeeded in the excitation to the Rydberg states from the $^3P_2$ state for atomic clouds with typically 10^5 atoms. This $^3P_2$ state has long lifetime of the order of seconds. The choice of the metastable state enables coherent one-photon transitions from the ground state and to Rydberg states, which suppresses decoherence compared with two-photon excitation method used in alkali atoms [4]. With this new excitation scheme to use the $^3P_2$-Rydberg states, we observed the spectra associated with target Rydberg states (6s)(*nd*) ^3D_J (J=1,2,3) and (6s)(*ns*) $^3S_1$, and also their response to an applied electric field.

We are now working on combining these two experiments, that is to say, we are trying to perform coherent excitation of single Ytterbium atoms to the $^3P_2$ state and Rydberg states, which is an important step towards the demonstration of quantum gate operation on single Ytterbium atoms.

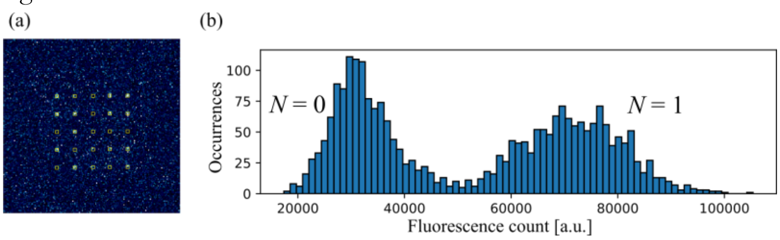

Figure 1: (a) An image of single atoms trapped in a 5x5 trap array. Yellow squares represent region of interests (ROIs) for each trap site. (b) A histogram of the fluorescence count in each site.

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Exotic superconductivity associated with parity symmetry breaking

Condensed Matter Theory Group　　Shota Kanasugi

Abstract Superconductivity associated with parity symmetry breaking has been attracted much attention owing to its exotic properties such as nontrivial topology and nonreciprocal transport. In this work, we clarify a variety of novel interplay between superconductivity and parity symmetry breaking from fresh viewpoints.

Unconventional superconductivity is one of the central topics in modern condensed matter physics. In particular, exotic superconducting phenomena induced by *parity symmetry breaking* is attracting much attention since the discovery of noncentrosymmetric (NCS) superconductors [1]. Although the interplay of superconductivity and parity symmetry breaking has been elucidated mainly for NCS superconductors, we can consider other types of superconductors associated with parity symmetry breaking; (i) superconductors coexistent with other parity-breaking orders, (ii) locally NCS superconductors, and (iii) superconductors hosting multiple even- and odd-parity pairing instabilities. However, theoretical understanding for such superconductors is still insufficient compared with that for NCS superconductors.

In this work, we investigate the above three types of exotic superconductivity associated with parity symmetry breaking. Summaries of each study are shown below.

1. Ferroelectric superconductivity and multiorbital/multiband effects **[2,3]**

We study a coexistent phenomenon of superconductivity and ferroelectric-like polar parity-breaking order, that we name the ferroelectric superconductivity (FESC). In particular, we focus on $SrTiO_3$ as a possible candidate and demonstrate the impacts of the multiorbital/multiband effect on the FESC. By analyzing a multiorbital model for $SrTiO_3$, we show that the FESC is stabilized in a very low carrier density regime or high magnetic field regime. Furthermore, we predict that the FESC in $SrTiO_3$ leads to Weyl superconductivity and odd-frequency pairing.

2. Odd-parity superconductivity in locally noncentrosymmetric crystals with ferromagnetic fluctuations **[4]**

We clarify the novel interplay of ferromagnetic-fluctuation-driven odd-parity superconductivity and locally NCS crystal structure. To this end, we consider a bilayer triangular lattice Hubbard model relevant to bilayer transition metal dichalcogenides. By analyzing this model, we demonstrate that multiple odd-parity pairing instabilities are induced owing to the combination of locally NCS crystal structure and ferromagnetic fluctuation. The results shed light on the possibility of odd-parity superconductivity in ferromagnetic van der Waals materials.

3. Anapole superconductivity from PT-symmetric mixed-parity interband pairing **[5]**

We explore time-reversal-symmetry-breaking mixed-parity superconductivity, which can be stabilized when the even- and odd-parity pairing instabilities are competing in one system. We show that such superconducting states generally exhibit an unusual asymmetric Bogoliubov spectrum in multiband systems. We also demonstrate that the asymmetric Bogoliubov quasiparticles lead to the effective anapole moment of the superconducting state, which stabilizes a nonuniform FFLO-like superconducting state at zero magnetic fields. Furthermore, we apply our theory to a recently discovered superconductor UTe_2.

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Probing three-state Potts nematic fluctuations by ultrasound attenuation

Kazuhiro Kimura (Condensed Matter Theory Group)

Abstract Motivated by recent studies of three-state Potts nematic states in magic-angle twisted bilayer graphene and doped-Bi_2Se_3, we analyze the impact of critical nematic fluctuations on the low energy properties of phonons. In this study, we propose how to identify the three-state Potts nematic fluctuations by ultrasound attenuation.

Recent discoveries of electron-nematic phases, which break a certain point group symmetry of the system, have suggested that the superconducting pairing mechanism may be closely related to nematicity in some correlated electron systems. Obviously, the relation between electron-nematic order and unconventional superconductivity is a pressing question in present condensed matter physics.

In the case of magic-angle twisted bilayer graphene [1], an electron-nematic state, which breaks the lattice C_{3z} symmetry, has been detected [2]. This C_{3z}-broken electron nematic state, referred to as a three-state Potts nematic state, is of interest for its competition [2] with nematic superconductivity and for the mystery of the Landau level degeneracy [1]. Moreover, in the case of doped-Bi_2Se_3, which is a candidate material of nematic superconductors [3], a three-state Potts nematic state has been reported above the superconducting transition temperature [4]. Besides the relationship between nematicity and superconductivity, it is also important to identify the critical behavior of electron-nematic states and to distinguish whether it is intrinsic (i.e. induced spontaneously) or extrinsic (i.e. due to trivial strains or the structural distortion).

We investigate [5] the influence of the nemato-elastic coupling on the low energy properties of phonons by a phenomenological argument using a Ginzburg-Landau-Wilson action and a microscopic analysis based on the Hubbard model. The Gaussian fluctuation analysis shows an isotropic divergence of the transverse sound attenuation coefficient, in contrast to the case of the C_4-breaking bond-order which shows the strong anisotropy [6]. Moreover, we use a mean-field approximation and discuss the impurity effects. With increasing the impurity scattering, the first-order transition line (see Fig. 1) at low temperatures gradually shifts towards the second-order transition line, rendering the transition a weak first-order. Finally, we expect that the enhancement of the ultrasound attenuation coefficient will be clearly observed in the case of the intrinsic electron-nematic phase transition, even if it is a weak first-order transition.

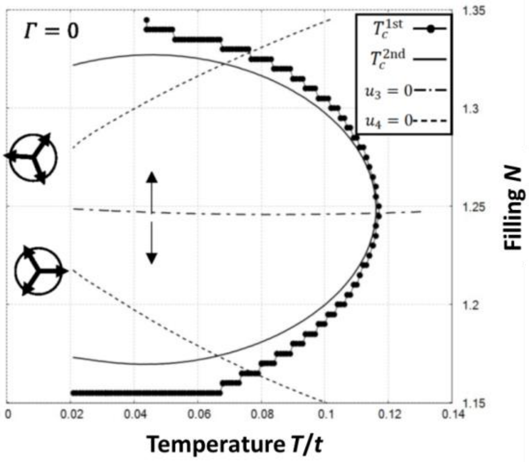

Fig. 1. Phase diagram of a nematic bond-ordered state near the van-Hove filling (N = 1.25). T_c^{1st} (T_c^{2nd}) is the first (second) order phase transition line. Two different nematic configurations are shown as the three arrowheads surrounded by the circle, which is divided by u_3=0 line.

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Role of incoherent carriers in high harmonic generation from atomically thin semiconductors

Solid State Spectroscopy Group　　Kohei Nagai

Abstract We have studied photo-carrier doping effects on high harmonic generation in monolayer WSe_2 by pump and probe spectroscopy. The doping-induced effects suggest that high harmonic generation is governed by the incoherent carriers that are originally generated by the strong driving field in addition to the photo-carriers.

Non-perturbative interaction between strong laser field and solid triggers various coherent electron dynamics, such as Zener tunneling, Bloch oscillation, and also formation of Floquet state [1,5]. High harmonic generation (HHG), which converts low-energy photons to visible to ultraviolet photons, offers a powerful experimental tool to understand the coherent electron dynamics [1-5]. Many theoretical studies have predicted that inter- and intra-band currents created by strong-field driven coherent and incoherent carriers in momentum space radiate high harmonics in solids [1]. In experimental studies, HHG has been mainly investigated for bulk crystals [1,2]. However, propagation effects in bulk solids obscure the intrinsic harmonic spectrum, which hinders the study of microscopic mechanisms. To avoid such difficulty, atomically thin semiconductors are an ideal platform [3-5]. Although HHG from monolayer transition metal dichalcogenides has been successfully explained by inter- and intra-band currents [3,4], there remain several unclear problems; interplay between these mechanisms and also many body effects under strong laser field.

In this study, we experimentally distinguish the role of incoherent carriers in high harmonic generation by using photo-carrier doping [2]. We fabricated single monolayer WSe_2 by mechanical exfoliation. Incoherent carriers with the density of 10^{12}-10^{13} cm^{-2} were injected into the sample by near-infrared (NIR) pulses that are resonant with the absorption edge of the monolayer (photon energy: 1.63 eV, bandwidth: 10 nm). After the decoherence process of the photo-carriers, intense mid-infrared (MIR) pulses (photon energy: 0.26 eV, pulse duration: 60 fs, peak intensity: 0.24 TW/cm^2) were shined to generate high harmonics from the photo-doped samples (Fig. 1(a)).

We observed the harmonics from the 5th to 12th order under the MIR driver. Under the photo-carrier doping, a small enhancement of the 5-th order harmonics (below the absorption edge) and large suppression of higher harmonics (above the absorption edge) were confirmed as shown in Fig. 1(b). Theoretical calculation using semiconductor Bloch equation indicates that the enhancement of the 5th order harmonics is originated from the intraband acceleration of photo carriers. Also, excitation-induced dephasing significantly decrease higher-order interband harmonic yield. Our work reveals that high harmonic generation is governed by the incoherent carriers that are originally generated by the strong driving field in addition to the photo-carriers. They create additional contribution to the intraband current relevant to lower-order harmonics and significantly suppress the interband polarization that contribute to higher-order harmonics than the absorption edge.

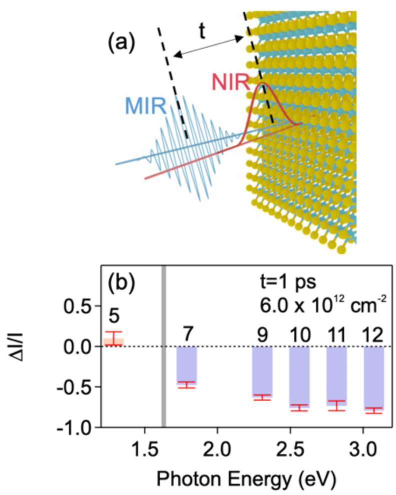

Fig. 1. (a) Setup of photo-carrier doping experiment for high harmonic generation. (b) Differential harmonic yield under the photo-doping.

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Game-theoretic derivation of Gibbs distribution

Nonlinear Dynamics Group Ken Hiura

Abstract We propose a sequentially predictive form of the work extraction process. In this formulation, an external agent repeats cyclic operations infinitely many times and extracts work from a heat engine. We prove that if we impose the second law of thermodynamics in this situation, the empirical averages of relevant variables must converge to the equilibrium values determined by the Gibbs distribution.

A thermodynamic theory for mesoscopic systems that are weakly coupled to equilibrium environments, called stochastic thermodynamics, has been developed over the past two decades and it provides universal relations that are valid even far from equilibrium such as the fluctuation relations and the Jarzynski equalities. In recent years, it was found that a game-theoretic approach to stochastic thermodynamics based on martingale theory sheds light on novel properties in non-equilibrium systems including the stopping time statistics and extreme value statistics [1].

In this presentation, we study the fundamental aspect of statistical mechanics from the viewpoint of martingale theory as another possible direction of the game-theoretic approach. Specifically, we investigate how the probabilistic description on the Gibbs distribution emerges from the second law of thermodynamics [2].

It is known that we cannot extract a strictly positive amount of work on average through any cyclic operation if the heat engine is prepared initially according to the Gibbs distribution [3]. In this presentation, we address the inverse problem: Whether the second law conversely characterizes the Gibbs distribution or not. To this end, we propose a sequentially predictive formulation of the work extraction where an external agent repeats the extraction of work from a heat engine by cyclic operations based on his predictive strategy (Fig.1). We find that the process of the exponential of the accumulated work under a strategy is identified with a martingale process. Based on this finding, we show that if we impose the second law of thermodynamics in this situation, the empirical distribution of the initial microscopic states of the engine must converge to the Gibbs distribution of the initial Hamiltonian under some strategy, even though no probability distributions are assumed. We also propose a protocol where the agent can change only a small number of control parameters. We find that in this situation the sequentially predictive form of the second law of thermodynamics implies the strong law of large numbers of the conjugate variables with respect to the control parameters (Fig.2).

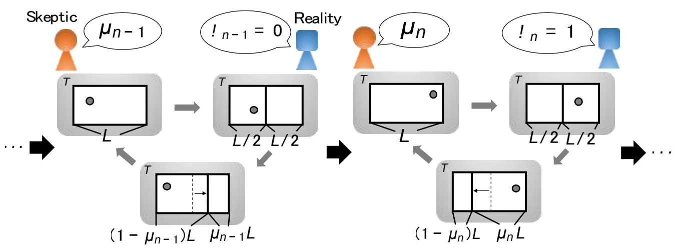

Fig.1: Schematic of the sequentially predictive protocol in single-particle ideal-gas engine

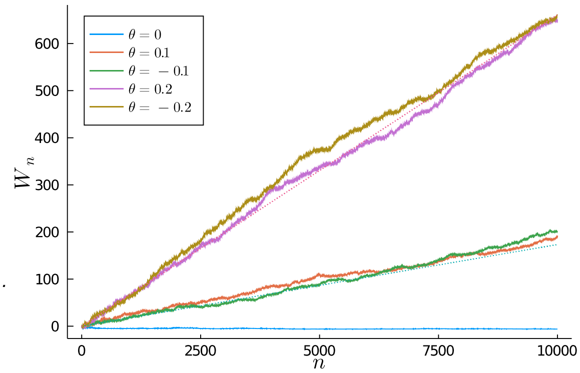

Fig. 2: Accumulations of extracted work for sequences generated by the Gibbs distributions with various parameters versus the number of cycles.

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Stochastic growth of a stable phase from a metastable phase

Nonlinear Dynamics Group Hiraizumi Mao

Abstract We propose a stochastic model describing the phase growth accompanying latent heat. By studying the model on a sparse-randomly lattice, we can identify the metastable phase in addition to the equilibrium properties. Performing numerical simulation, we find that the growth law is qualitatively different from that of the deterministic model.

When a metastable phase contacts with a stable phase, the stable phase grows and eventually the metastable phase vanishes. The phenomenon can be described by the time evolution of an order-parameter field that represents the extent of the order. When the order parameter is the only relevant dynamical variable of the system, the solution of the propagating interface is easily determined. However, when latent heat is generated in the phase growth, the temperature field evolve, and the order parameter field is also affected accordingly. The set of coupled equations is called the phase field model. It has been known that the displacement of the planar interface is proportional to the square root of the time interval when the extent of the metastability is less than unity. The behavior was numerically observed [1] and recently it has been derived by a systematic perturbation method [2].

However, it is not obvious whether or not the phase-field model is appropriate for describing phase growth. Following the Onsager principle, we can derive an equation equivalent to the phase-field model. Since the noise intensity is determined by the fluctuation-dissipation relation of the second kind, the thermal noises are inevitable in the description. Moreover, a typical interface width is on the order of 10^{-7}cm. Thus, the interface may be out of the mesoscopic description. In the phase-field model, all such properties are universally represented by only the gradient term.

In this presentation, we propose a statistical mechanics model describing the phase growth accompanying latent heat. The model we study is the q-states Potts model with an additional variable representing kinetic energy at each site. For this model on a sparsely random model only in one direction, we calculate the stable and metastable phases exactly in statistical mechanics. We perform numerical simulation to measure the behavior of the interface in two dimensions. We find the scaling relation $R(t) = L_x\bar{\mathcal{R}}(Dt/L_x^2)$ with large L_y fixed [3]. The scaling function $\bar{\mathcal{R}}(z)$ shows $\bar{\mathcal{R}}(z) \sim z^{0.5}$ for $z \ll z_c$ and $\bar{\mathcal{R}}(z) \sim z^{\alpha}$ for $z \gg z_c$, where the crossover value z_c and the exponent α depends on the temperature of the heat bath in contact with the stable phase. The latter scaling relation is not observed in the phase field model. This result indicates that the stochastic phase growth provides a different universality class from that described by the phase-field model.

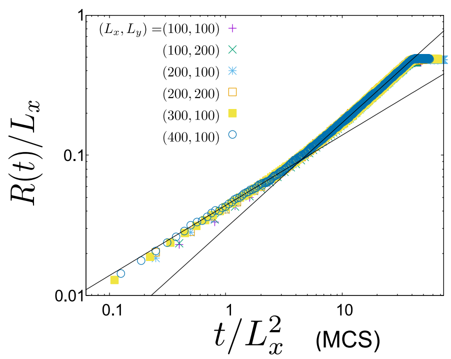

Fig. 1. One example of the numerical result. Log-log plot of R/L_x as a function of $z = t/L_x^2$. The two guidelines represent $h(z) \sim z^{0.5}$ and $h(z) \sim z^{0.75}$.

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Extended Nielsen-Ninomiya Theorem for Floquet and non-Hermitian Systems

Yukawa Institute for Theoretical Physics　Takumi Bessho

Abstract We find an extended version of Nielsen-Ninomiya theorem for Floquet systems and non-Hermitian systems. As an application, we propose two novel physics. The one is non-Hermitian chiral magnetic effect, and the other is extrinsic boundary states in quantum walks.

Recently, the study of topological phases has made great progress on highly-controlled nonequilibrium systems: One is a Floquet system governed by a time-periodic Hamiltonian, and another is a non-Hermitian system where an open quantum or classical system effectively obeys a non-Hermitian Hamiltonian. Floquet systems and non-Hermitian systems are not only desirable platforms to effectively realize topological insulators and superconductors but also novel platforms to realize unique topological physics that have no counterpart in equilibrium. A unique physics is the breakdown of Nielsen-Ninomiya theorem assuring a pair-wise creation and annihilation of gapless modes. In Floquet systems, two different schemes to realize a single Weyl mode were proposed [1,2]. In non-Hermitian systems, a general scheme to obtain a single gapless mode was proposed [3]. Although recent topological classifications [4-7] have clarified the existence or absence of topological invariants in each symmetry classes and dimensions, they do not provide precise relations between topological invariants and various topological phenomena. In the present talk, we establish a general theory that gives a precise relation between the topological invariants and the single gapless modes.

1. Extended Nielsen-Ninomiya theorem [8]

In this study, we find and prove formulae of net gapless modes and topological invariants in Floquet and non-Hermitian systems in a unified manner. For non-Hermitian systems, we refined an observation given by Lee, *et al.* [3] into a formula, i.e., extended Nielsen-Ninomiya theorem for non-Hermitian systems. For Floquet systems, we established a topological duality between Floquet and non-Hermitian systems, and applied the duality to the non-Hermitian formula to obtain the extended Nielsen-Ninomiya theorem for Floquet systems.

2. Non-Hermitian chiral magnetic effect [8]

As an application of the extended Nielsen-Ninomiya theorem for non-Hermitian systems, we propose a chiral magnetic effect by utilizing non-Hermitian spin-selective loss. While the original chiral magnetic effect uses the chiral potential unbalance, our non-Hermitian chiral magnetic effect uses the difference in the imaginary part of the energy indicating loss or amplification. We also find a formula of net chiral modes under magnetic field.

3. Extrinsic topology in quantum walks [9]

As an application of the extended Nielsen-Ninomiya theorem for Floquet systems, we point out extrinsic topology in quantum walks. We give a topological classification of boundary states in quantum walks, and show that the half of boundary states depend on boundary topology rather than bulk topology.

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Theoretical study on
Nonequilibrium many-body phenomena in Floquet systems

Kaoru Mizuta, Condensed Matter Theory Group

Abstract Floquet systems provide attractive platforms for novel nonequilibrium phases. However, generic Floquet interacting systems suffers from the trivial infinite-temperature steady states due to the heating problem. We have explored nontrivial dynamics and steady states in Floquet interacting systems beyond the heating problem, exploiting quasi-steady states, dissipation, and many-body scars.

Floquet systems, where the Hamiltonian varies periodically in time, have become one of the most important nonequilibrium platforms in the past decade. They provide phases of matter inherent in nonequilibrium, such as time crystals, and various ways to control materials dubbed Floquet engineering. One of the today's central questions in Floquet systems is what kind of nonequilibrium phenomena can take place under interactions and periodic drives, or equivalently by the interplay of many-body and nonequilibrium properties. For tackling this problem, Floquet-ETH plays a significant role, which dictates that isolated Floquet interacting systems generally relax to trivial infinite-temperature states. Thus, in order to find out nontrivial dynamics or steady states in Floquet interacting systems, we should overcome the trivial physics predicted by Floquet-ETH.

In our study, we have explored the following two cases violating the assumptions of Floquet-ETH to avoid its trivial physics:

(a) Quasi-steady states of Floquet interacting systems in the resonant regime [1,2],

(b) Dissipative dynamics of Floquet interacting systems in the high-frequency regime [3].

In the first case (a), while the genuine steady state is still trivial, we have shown that Floquet interacting systems can host nontrivial quasi-steady states with a sufficiently long lifetime. We have clarified the effective Hamiltonian for the quasi-steady states when the resonant drive gives a local Z_N-symmetry, implying that the systems emergently obtain a robust Z_N-symmetry. This result can be applied to the analysis of time crystals in quasi-steady states [1] and resonant Floquet engineering, simultaneously controlling phases and symmetries [2]. In the second case (b), we have explored dissipative Floquet interacting systems, breaking the isolation. When focusing on the high-frequency regime, isolated Floquet systems are always equivalent to isolated static systems. By analyzing whether the high-frequency expansion is a Liouvillian, we have discovered that dissipative Floquet interacting systems generally have no static counterparts in contrast to isolated cases. This implies unique behaviors brought by the interplay of dissipation, periodic drive, and interactions. We also note that Floquet-ETH is just a conjecture verified numerically and experimentally, leaving the possibility of nontrivial physics without violating the assumptions of Floquet-ETH. This have motivated us to seek for

(c) Athermal dynamics and steady states of isolated nonintegrable Floquet interacting systems.

By exploiting quantum many-body scars recently observed in Rydberg atoms, we have succeeded in composing a periodically-driven model under Rydberg blockade becoming a counterexample to Floquet-ETH [4]. This elucidates the possibility of nontrivial quantum many-body phenomena in generic Floquet interacting systems.

In the presentation, after introducing the overview of Floquet systems and our studies, we will concentrate on our results in Floquet quantum many-body scars [4].

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Non-Hermitian aspect of strongly-correlated electron systems

Condensed Matter Theory Group, Yoshihiro Michishita

Abstract:
In this talk, we derive the effective non-Hermitian Hamiltonian in the context of strongly-correlated electron systems and show its equivalence to the effective non-Hermitian Hamiltonian in the context of open quantum systems. Furthermore, we analyze the Kondo physics and nonlinear transport from non-Hermitian point of view.

Non-Hermitian physics describes the dynamics of the system in which energy and particle number are not conserved. It often emerges in open systems [1], such as photonics [2,3], cold atoms [4], and active matters [5].

The pioneering work [6] by Shen and Fu has shown that strongly-correlated electron systems (SCES) can also be described by the effective non-Hermitian Hamiltonian. This statement holds the possibility that the non-Hermitian phenomena seen in photonics or cold atoms can also be seen in SCES, and they can be understood from the unified description by non-Hermitian matrices. However, the circumstances and requirements for the emergence of the non-Hermitian phenomena are entirely different in open systems and SCES, and the relation between each description was unclear.

In this talk, we first show that the effective non-Hermitian Hamiltonian emerging in both fields are identical by describing SCES as an open quantum system [7]. Then we investigate the Kondo physics, which is one of the primary topics in SCES, from the point of view of non-Hermitian physics, and show that it can be understood as the topological change of the exceptional manifolds in the momentum-frequency space [8]. Finally, we analyze the non-Hermitian effect on the linear and nonlinear transport in SCES and elucidate the effective enhancement of lifetime by the non-orthogonality of eigenstates and the sign change due to the imaginary gap by the non-Hermitian effect [9,10].

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Novel quantum phases accompanied by rotational symmetry breaking in strongly correlated electron systems

Quantum condensed matter group Hinako Murayama

Abstract By performing magnetic torque measurements, we have revealed novel quantum phases accompanied by rotational symmetry breaking in two strongly correlated materials. One is the diagonal nematic order in a high-T_c cuprate superconductor $HgBa_2CuO_{4+\delta}$, and the other is the anapole order in a spin-orbit assisted Mott insulator $Sr_2Ir_{1-x}Rh_xO_4$. (50 words)

The main issue in solid-state physics has been the investigation of exotic electronic orders and their phase transitions accompanied by various types of symmetry breaking. An intriguing example is the liquid-solid transition of electrons in strongly correlated systems; in a metal, electrons move around with interaction like a liquid while they become frozen and arranged on a lattice like a solid by the strong repulsion. Recently, the emergence of new electronic orders breaking the rotational symmetry between the liquid and the solid, which are called nematic orders on the analogy of the nematic crystal liquid, has attracted much attention. Here we report two examples of the nematic orders. The rotational symmetry breaking was probed by ultra-precision measurements of anisotropy in magnetic torque. As the magnetic torque is a thermodynamic quantity, it provides thermodynamic evidence for the phase transition, sensitively detecting the rotational symmetry of the order parameter.

The first finding is the nematic order in hole-doped cuprates [1,2]. Carrier doping on cuprates suppresses the Mott insulating phase and induces superconductivity. In hole-doped cuprates, the pseudogap, a partial gap opening at the Fermi level, appears well above the superconducting transition temperature T_c. It has been widely believed that the pseudogap phenomenon is closely related to the mechanism of the high-T_c superconductivity. Despite tremendous research, however, the nature of the pseudogap state has been elusive. The most controversial issue is whether the pseudogap formation is a cross-over phenomenon or a phase transition. At an early stage, the pseudogap state has been attributed to a precursor of superconductivity. On the other hand, recent studies report the observation of symmetry breakings in the pseudogap state, suggesting the phase transition at the pseudogap onset temperature. We performed magnetic torque measurements on tetragonal $HgBa_2CuO_{4+\delta}$ and revealed that electrons exhibit the two-fold in-plane rotational symmetry in the pseudogap state [2]. This provides the thermodynamic evidence for the phase transition accompanied by rotational symmetry breaking at the pseudogap onset temperature. The nematic order parameter orients to the Cu-Cu bond direction, rotating by 45 degrees from that in the orthorhombic $YBa_2Cu_3O_y$ [1]. The nematic order in $HgBa_2CuO_{4+\delta}$ is called the diagonal nematic order, which is distinct from the nematic order along the Cu-O-Cu bond direction in $YBa_2Cu_3O_y$.

The second finding is the anapole order in a spin-orbit assisted Mott insulator Sr_2IrO_4[3]. The strong spin-orbit interaction of Ir 5d orbitals effectively enhances the correlation effect, resulting in the Mott insulating state for the ground state of Sr_2IrO_4. The slight Rh substitution of Ir dopes hole carriers, suppressing the Mott insulating phase. The appearance of the hidden order phase, in which inversion and time-reversal symmetry breaking occurs, has been reported in the vicinity of the Mott insulating phase. However, the nature of the hidden order phase was is largely unexplored. We conducted magnetic torque measurements on $Sr_2Ir_{1-x}Rh_xO_4$. We find that the hidden order also breaks the rotational symmetry. We point out the possibility that those symmetry breakings are induced by a new type of electronic order in which nano-loop current flows between atoms. This order is an anapole order whose order parameter resembles the anapole in nuclear physics.

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