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Ｄ Ｃ ３ 回 生 研 究 発 表 会
要旨集

２０２５年１１月２１日（金）

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発表：２０分（別に質問１０分程度）

２０２５年１１月２１日（金）９：００～　開始

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Ultrafast carrier dynamics in the excitonic insulator Ta_2NiSe_5

Solid State Spectroscopy Group　　Katsuki Morimoto

Abstract We investigated the ultrafast carrier dynamics on the 10 fs timescale in the excitonic insulator Ta_2NiSe_5 by sideband generation spectroscopy. Our observations and calculations suggest that the low-energy boson from the excitonic condensation contributes to the decoherence process of photocarrier pairs.

Revealing ultrafast dynamics in solids has been at the frontier of condensed matter physics as it enables us to access the elementary processes by which matter interacts and evolves on its intrinsic timescales. In typical semiconductors, ultrafast carrier dynamics have been explored through coherent nonlinear optical responses under strong light fields and are well described within the single-electron approximation. By contrast, in strongly correlated electron systems, the single-electron approximation breaks down due to strong Coulomb interactions between electrons. Since carrier–carrier interactions play a dominant role, it is expected that correlations influence ultrafast carrier dynamics on the timescale governed by carrier–carrier scattering, which is typically on the order of 10 fs [1]. However, such correlation effects remain largely elusive [2-4].

In this study, we investigated the ultrafast carrier dynamics in the excitonic insulator Ta_2NiSe_5 [5], using the sideband generation technique [6]. Excitonic insulators are strongly correlated electron systems and have energy gaps that emerge from the spontaneous condensations of bound electron-hole pairs (excitons). Sideband generation is a frequency mixing process of photocarrier creation pulses and intense driving pulses ($\hbar\omega_n = \hbar\omega_{creation} + n\hbar\omega_{driving}$; n is an integer), originating from ultrafast coherent photocarriers dynamics induced by the driving pulses. In our experiments, to probe the excitonic order effect, the creation pulses selectively generated photocarriers around the valence band top, where carriers spontaneously form excitons in the ground state. By employing driving pulses with periods on the order of 10 fs, the resulting sideband spectra reflect carrier dynamics occurring on comparable timescales and thus provide insight into the ultrafast processes under the excitonic order.

Figure 1(a) shows the temperature dependence of the sideband emission intensity at n = 2 with $\hbar\omega_{creation}$ = 1.55 eV and driving periods $2\pi/\omega_{driving}$ = 16.5 fs, 25.8 fs, and 29.5 fs. A stronger intensity reduction is observed with longer driving periods. Since the emission arises from the coherent dynamics of photocarrier pairs, this temperature dependence suggests that excited photocarrier pairs have shorter scattering time at higher temperatures. Our phenomenological model, which assumes a scattering process with a bosonic quasi-particle, qualitatively reproduces the experimental trends as shown in Fig. 1(b), with scattering time varying from 12 fs to 4 fs in the calculations. Our results suggest a low-energy boson strongly coupled to carrier dynamics, which does not exist in typical semiconductors, associated with the excitonic condensation in Ta_2NiSe_5.

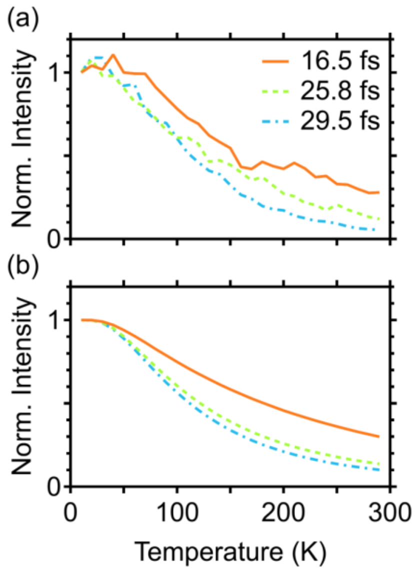

Fig. 1 (a) Observed temperature dependence of sideband emission intensity (n = 2). (b) Calculated emission intensity, corresponding to (a).

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Texture of Superfluid ^{3}He in Cylindrical Geometry

Laboratory of Low Temperature Physics Xu Zeju

Abstract In large cylindrical sample cell, stable domain walls were observed in A phase. The observed frequency shift agrees with the theoretical estimation for ℓ-soliton. Thicker domain walls and hyperbolic-texture were observed in B phase, as well as localized spin waves trapped in the texture.

Compared with superfluid ^{4}He, whose order parameter is scalar, superfluid ^{3}He has attracted considerable attention because of its complex tensor order parameter. In superfluid ^{3}He, the order parameter displays both spin and orbital symmetries, characterized by ℓ and d vectors in A phase and the relative symmetry by an **n** vector in B phase. In a confined space, these invisible vectors in superfluid ^{3}He are re-oriented by both boundary condition of sample cell walls and external field such as magnetic field and flow. Since textures cannot be observed directly, we use NMR/MRI techniques, which allow us to measure the frequency shift caused by the texture and thereby indirectly detect its presence. In this way, the spatial variation of these vectors, which is confined between walls or under the conditions mentioned above, can be better understood. The information of the actual texture is important for precise study of the order parameter in superfluid ^{3}He.

Previous experiments [1,2] were performed in the 100-μm-gapped parallel plates cell, which is 10 times larger than the typical spatial variation length scale of textures. In such a narrow space, one can limit the possible symmetry of textures. Thanks to this simplification, they could study the structure of various domain walls in the A phase. In order to study the texture and domain wall in much larger space, we studied superfluid ^{3}He in 1mm-Φ-cylinder sample cell. Firstly, we are interested in determining whether the domain wall remain stable in such a large sample in the A phase. Secondly, we investigate whether domain wall, can be observed in the B phase. Finally, we aim to explore the behavior of spin waves in the non-uniform texture of B phase.

In the A phase, spontaneous formation of aligned domain walls are observed along axis direction of the cylinder (Fig. 1). These are considered to hold thin-wall-like structures between domains with different symmetries. Such structures are stable in their locations and numbers, and do not change with time, when the temperature is far from the transition temperature within the A phase. Furthermore, the expected frequency shift, which reflects the spatial variation of the texture, agrees with the theoretical estimation for ℓ-soliton [3]. However, due to a limited measurement accuracy, the precise type of the ℓ-soliton (whether twist or splay) cannot be determined.

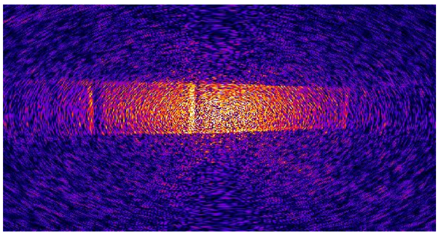

Fig. 1 Domain walls in A phase

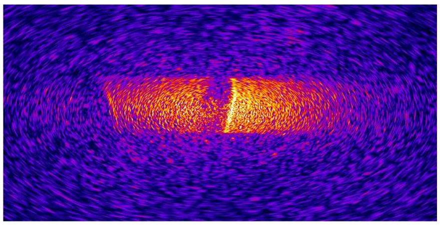

Fig. 2 Domain walls in B phase

In the B phase, domain walls that are thicker than those in the A phase are observed (Fig. 2). These domain walls remain stable. In the absence of domain walls, hyperbolic- texture in the cross-section of the cylinder is confirmed. Localized spin waves which are trapped in the texture are detected.

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Precision isotope shift measurements of neutral ytterbium atoms toward new physics search

Quantum Optics Group Taiki Ishiyama

Abstract We measure isotope shifts of three ultra-narrow optical transitions in neutral ytterbium atoms at 10^{-9} precision. Notably, this includes the first observation and precision spectroscopy of an inner-shell orbital clock transition $4f^{14}6s^2\ ^1S_0 - 4f^{13}5d6s^2$ ($J = 2$). Furthermore, we discuss possible insights into a new Yukawa-type interaction between electrons and neutrons.

The Standard Model (SM) is the fundamental physical theory, providing an excellent explanation for almost all particle-physics phenomena in our universe. However, it is also recognized as incomplete, because some phenomena, such as dark matter, escape from proper explanation. To search for new physics beyond the Standard Model, low-energy precision measurement experiments have been actively conducted [1] as a complementary approach to high-energy accelerator experiments, such as the Large Hadron Collider.

In 2017, Ref. [2] proposed that a new Yukawa-type interaction between electrons and neutrons might be detected via precise isotope shift (IS) measurements (Fig 1(a)). To avoid large theoretical uncertainty in atomic energy calculation, the proposal relies on the linear relation between ISs of multiple electronic transitions, known as (generalized) King linearity [3,4], which might be violated by the new particle. Moreover, this IS data can provide useful information about nucleus, especially higher moments of nuclear charge distribution [5]. To obtain new insights into particle and/or nuclear physics, it is crucial to measure the ISs of as much as electronic transitions and isotope pairs with high precision.

Here, we report IS measurements of three ultra-narrow optical transitions in neutral ytterbium (Yb) atoms at 10^{-9} precision (Fig 1(b)) [6-8]. In the first part of my presentation, I focus on that of an inner-shell clock transition $4f^{14}6s^2\ ^1S_0 - 4f^{13}5d6s^2$ ($J = 2$), enabled by our first observation and precision spectroscopy (Fig 1(c)) [9]. In the second part, by combining our data with those of two ultra-narrow transitions in Yb^+ [10], we present the King plot analysis to obtain new insights for a new Yukawa-type interaction under reasonable assumptions.

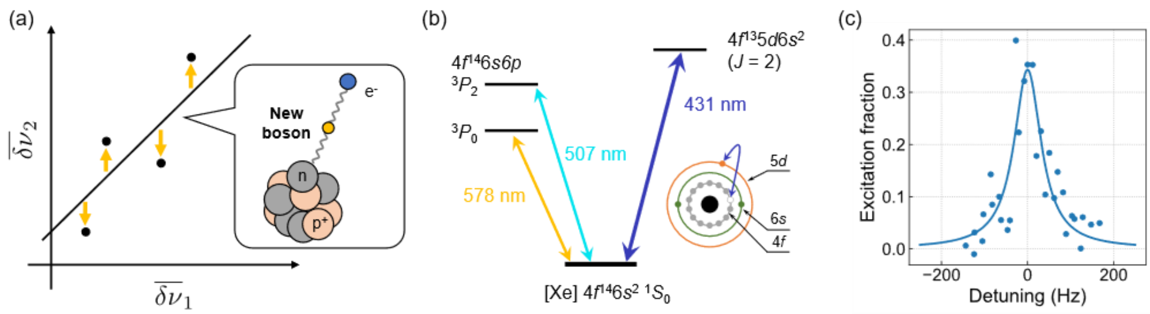

Fig 1 (a) Schematic of new boson search by King linearity test. (b) Three ultra-narrow optical transitions in neutral Yb atoms. (c) Precision spectroscopy of the $4f^{14}6s^2\ ^1S_0 - 4f^{13}5d6s^2$ ($J = 2$) transition at 431 nm. The blue solid line is a Lorentzian fit, yielding full width at half maximum of 77(11) Hz.

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The superconducting multiphase and magnetism in locally inversion symmetry breaking superconductor $CeRh_2As_2$

Quantum Materials Laboratory Shiki Ogata

Abstract We performed nuclear quadrupole resonance and nuclear magnetic resonance measurements on $CeRh_2As_2$ and revealed that the magnetic structure in the antiferromagnetic state is an A-type antiferromagnetic state with incommensurate modulation. Knight-shift measurements revealed that the low-field and high-field superconducting phases correspond to even- and odd-parity superconducting states, respectively.

$CeRh_2As_2$ is a heavy-fermion superconductor with a superconducting (SC) transition temperature $T_{SC} \sim 0.3$ K, which exhibits the SC multiphase under the c-axis field, featuring a distinct phase boundary at $\mu_0 H^* \sim 4$ T [1]. As shown in Fig. 1, $CeRh_2As_2$ has global inversion symmetry, while the local inversion symmetry is broken at the Ce site. In superconductors with locally broken inversion symmetry, a low-field even-parity SC state and a high-field odd-parity SC state have been theoretically proposed [2]. The SC multiphase in $CeRh_2As_2$ can be understood as a result of these two states. However, no experimental evidence had previously been obtained for the parity transition within the SC multiphase. In addition to the SC multiphase, anomalies in the specific heat and thermal expansion at $T_0 \sim 0.4$ K have been reported [3], and we have reported the appearance of internal field below $T_N \sim 0.25$ K [4], which attracted further interest in this compound. We performed ^{75}As-nuclear quadrupole resonance (NQR) and nuclear magnetic resonance (NMR) measurements to investigate the magnetic and SC properties in higher-quality single crystal of $CeRh_2As_2$.

Below T_N, a distinct splitting of the NQR spectrum at the As(2) site was observed, whereas only a broadening of spectrum was found at the As(1) site [5]. Together with the NMR results and the NQR spectral simulation, we determined that the magnetic structure in the antiferromagnetic (AFM) state in $CeRh_2As_2$ is A-type AFM state with incommensurate modulation [6]. In contrast, no significant changes in NQR spectra were detected below T_0, except for a reduction in the NQR signal intensity. This reduction indicates the enhancement of nuclear spin-spin relaxation rate. Considering these results alongside μSR measurements that reported the emergence of an internal field below T_0 [7], it is suggested that relatively slow fluctuations develop below T_0 and freeze out below T_N, indicating internal field (Fig. 2).

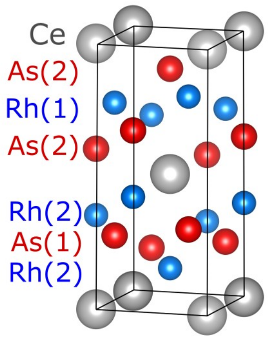

Fig. 1. The crystal structure of $CeRh_2As_2$.

We also measured Knight shift to investigate the spin state in the low-field SC phase (SC1) and the high-field SC phase (SC2) under the c-axis magnetic field [8,9]. We detected a clear reduction in the Knight shift in the SC1 phase, indicating an even-parity SC state. On the other hand, in the SC2 phase, although the Knight shift decreases near $\mu_0 H^* \sim 4$ T, it remains nearly constant under higher magnetic field than $\mu_0 H \sim 7$ T, suggestive of the odd-parity SC state. This provides the first experimental evidence of a SC parity transition in $CeRh_2As_2$.

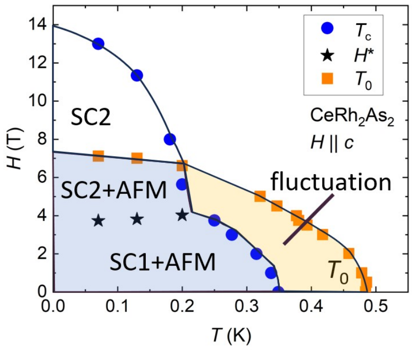

Fig. 2. H-T phase diagram of the $CeRh_2As_2$.

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Modified Amoeba Formulation for the Non-Hermitian Skin Effect in One-Dimensional Multiband Systems

Condensed Matter Theory Group　　Shin Kaneshiro

Abstract: The Amoeba formulation provides a powerful framework for analyzing the non-Hermitian skin effect in higher-dimensional systems. However, even in one-dimensional systems, its single-band foundation breaks down in multiband systems with symmetry-protected degeneracies; here we propose a modified, symmetry-resilient Amoeba formulation that restores its validity under class AII^{+} symmetries.

The concept of topology has become a central concept in modern condensed matter physics, providing profound insights into the qualitative behavior of quantum systems. In recent years, non-Hermitian physics has revealed a new frontier of topological phenomena beyond Hermitian systems. Among these, the non-Hermitian skin effect (NHSE), characterized by spectral winding and extreme sensitivity to boundary conditions even in the thermodynamic limit, stands out as a striking example. The NHSE invalidates conventional Bloch band theory, necessitating real-space diagonalization of large non-Hermitian matrices, often accompanied by severe numerical instabilities.

While the non-Bloch band theory [1,2] successfully describes the NHSE in one-dimensional systems, its generalization to higher dimensions remains a formidable challenge. The Amoeba formulation [3] provides a promising framework by introducing a spectral potential, obtained via optimization of the Ronkin function, to describe the NHSE in arbitrary dimensions. This approach, grounded in the strong Szegö limit theorem [4] and its topological generalization [3], is mathematically well established for single-band systems. However, in multiband systems, where the Ronkin function mixes contributions from multiple bands, symmetry-protected degeneracies can invalidate the original formulation even in one dimension.

In this study, we propose a modified Amoeba formulation that remains valid in the presence of certain symmetries, specifically a transpose-type time-reversal symmetry (class AII^{+}). First, we introduce the concept of symmetry-decomposed Ronkin functions [5], where the total Ronkin function is partitioned into independent symmetry sectors, allowing the spectral potential to be correctly optimized within each sector. Second, we establish the Wiener–Hopf factorization (WHF) of the non-Bloch Hamiltonian as a unifying mathematical framework for multiband Amoeba analysis [6]. By combining the WHF [7] with a doubled Hermitian Hamiltonian construction, we derive explicit applicability criteria for the generalized Szegö limit theorem in multiband systems. Finally, we demonstrate that the WHF naturally underpins the symmetry-decomposed Ronkin functions, thereby providing a proof of the generalized Szegő theorem for class AII^{+}.

Our results extend the mathematical foundation of the Amoeba formulation beyond the single-band regime, establishing a symmetry-resilient framework for studying the NHSE in higher-dimensional and multiband non-Hermitian systems.

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Quantum Computing with Ytterbium Atoms: Toward Implementing Hardware-Efficient Quantum Error Correction

Quantum Optics Group Toshi Kusano

Abstract We report the demonstration of unique techniques toward hardware-efficient quantum error correction. We develop (1) plane-selective manipulation of ^{171}Yb nuclear spin qubits in a three-dimensional optical tweezer array, and (2) coherent control of ^{173}Yb spin-cat qubit in a two-dimensional optical tweezer array.

Neutral atoms in an optical tweezer array (OTA) have emerged as a promising platform for quantum computation, quantum simulation, and precision measurement [1]. This system holds attractive features such as the scalability [2], high-fidelity control [3], and all-to-all connectivity with movable traps [4], enabling to implement quantum error correction (QEC) toward fault-tolerant quantum computing. Recent developments in this platform have achieved the below-threshold performance of a QEC code, opening the way to programmable operations at the logical level [5]. However, a gap still exists between utility-scale quantum computing and current technology, necessitating a more than 1,000-fold increase in the number of qubits. Furthermore, the operational speed of neutral atom platforms is approximately 1,000 times slower compared to superconducting qubits. Therefore, there is a demand for developing efficient quantum computing schemes that reduce both space- and time-overheads.

In this work, we demonstrate key techniques toward hardware-efficient quantum computing utilizing ytterbium (Yb) atoms trapped in an OTA, as summarized below.

1. ***Plane-selective manipulation of nuclear spin qubits in a three-dimensional optical tweezer array [6]***
   The extension of OTA platforms from the conventionally adopted two-dimensional (2D) array to a three-dimensional (3D) structure [7] is expected to enhance scalability in quantum processing. Furthermore, the 3D structure is advantageous for implementing time-efficient QEC codes, such as 3D topological codes [8], which offer benefits including the realization of transversal non-Clifford gates and the implementation of single-shot decoding. In our work, we realize local operations using global control applied across the entire 3D OTA. Specifically, we achieve coherent manipulation of the nuclear qubit with ^{171}Yb atoms and plane-selective initialization and shelving by utilizing the magnetic- field-sensitive metastable $^3P_2$ state under a magnetic field gradient. Our study facilitates controllability within 3D structures and opens the door to the realization of programmable 3D physical systems.
2. ***Spin-cat qubits with biased noise utilizing ^{173}Yb atoms [9]***
   Bias-tailored QEC codes [10] offer a higher error threshold than standard QEC codes and hold the potential to achieve lower logical errors with less spatial overhead. The spin-cat qubit [11] is a promising physical candidate that exhibits a noise structure biased towards Z errors, enabling the implementation of bias-tailored QEC codes. In this study, we demonstrate the coherent control of the spin-cat qubit encoded in the $^1S_0$ manifold of ^{173}Yb atoms. Using a single-beam Raman technique, we successfully generate the spin-cat state, implement covariant SU(2) rotations, and achieve single Clifford gates with a fidelity of 96.1(5) %. To evaluate the biased noise structure of the spin-cat state, we measure the T_2^* time and T_1 time and benchmark the noise bias of bias-preserving gates, which experimentally demonstrates that the spin-cat state is indeed biased towards Z error.

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Control Limits in Mutualistic Ecosystems

Statistical Physics and Dynamics Group   Ikumi Kobayashi

Abstract We study controllability in mutualistic ecosystems under constrained interventions. By controlling pollinator abundances, controllability is defined as the existence of a stability-preserving path between states. We then show a sufficient condition for the emergence of state pairs that remain inaccessible under any admissible intervention.

Controlling complex systems is a recurrent, fundamental problem across physics, chemistry, biology, and engineering. Typical examples include quantum-state manipulation, stabilization of chemical reaction networks, control of epidemic dynamics, and regulation of power and communication networks. A central question common to these settings is whether a system can be transformed from one state to another under given constraints—its controllability or reachability. Yet establishing a general theory for high-dimensional nonlinear systems is notoriously difficult: from the viewpoint of computational complexity, many decision problems in control are NP-hard or even undecidable, and the minimal actuator selection problem is NP-hard even for linear systems [1, 2].

Given these theoretical obstacles, we therefore restrict our attention to mutualistic ecosystems and analyze their reachability and control limits. Such ecosystems—e.g., plant–pollinator communities or host–microbe associations—are maintained by positive interspecific interactions that support biodiversity [3]. Because positive feedbacks can generate multiple stable states, small fluctuations in population sizes or slight environmental changes may trigger a community-wide collapse of abundances. To understand ecological resilience and to design recovery strategies, it is crucial to clarify whether a transition from a low-diversity state to a high-diversity coexistence state is feasible while maintaining stability.

Recent work developed a technique that reduces high-dimensional network dynamics in mutualistic ecosystems to one-dimensional effective dynamics [4]. Following this study, we represent the ecological state by a symmetric, nonnegative interaction matrix A that encodes plant–plant benefits induced by shared pollinators. In addition, we introduce pollinator abundances $\{u_i\}$ as control parameters under a total-budget constraint $\sum_i u_i \leq K$. We then define controllability from A_0 to A_1 as the existence of a continuous path along which the ecosystem remains stable at every point.

Under these settings, we derive a sufficient condition for inaccessibility, referred to as an uncontrollability theorem, that guarantees the existence of state pairs that cannot be connected by any admissible protocol. Specifically, this result clarifies the conditions under which it becomes impossible for the ecosystem to transform from a low-diversity state to a high-diversity state while maintaining stability. This result delineates, for mutualistic ecosystems, a region where safe control is feasible and a fundamentally uncontrollable region, specifying when attempts to increase biodiversity are excluded by structural and resource constraints.

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Physical Reservoir Computing Device Using Active Matter Made from a Swarm of Biomolecular Motors

Active Matter Lab　　Gong Yiming

Abstract We present a Physical Reservoir Computing system based on active matter made from swarm of biomolecular motors. By modulating local MT interactions through DNA hybridization, mediated by temperature and UV signals, swarm dynamics can be controlled to perform temporal information processing, with features of swarm patterns serving as output signals.

Reservoir Computing is a computational framework that exploits dynamical systems, which can respond to input signals, as resources for information processing. Extending this concept from *in silico* models to *in vitro* systems enables Physical Reservoir Computing (PRC), where actual physical stimuli such as temperature and photochemical signals can directly drive the dynamic of systems. Among various physical systems, active matter, an assembly of energy-consuming agents exhibiting collective motion, offers an ideal platform for realizing PRC due to its intrinsic nonlinearity and spatiotemporal complexity. For this purpose, this approach had been demonstrated using reservoirs composed of living organisms such as Tetrahymena [1], but their extendibility is limited. Here, we implemented a PRC device using swarming microtubules (MTs) driven by biomolecular motors [2], as shown in Fig. 1a, and compared the results with numerical simulations. Transitions between swarm and isotropic states were controlled by modulating local MT interactions through DNA hybridization, mediated by temperature and UV signals (Fig. 1b). The resulting spatiotemporal dynamics were recorded and analyzed using linear regression to capture the effect of local nonlinear interactions on the global MT swarm behavior.

Our results show that input signals effectively govern swarm dynamics, enabling controllable temporal information processing at the microscopic scale. Memory capacity, quantifying the reservoir's ability to store past inputs, was evaluated by training a linear regression model on recorded states to reconstruct delayed inputs (Fig. 1c). Compared with *Tetrahymena* reservoirs [1], the MT swarm PRC retained memory longer and was assessed using coefficient of determination (R^2 score) at finer temporal resolution. This work represents the first experimental realization of a swarm MT PRC system, providing a foundation for molecular-scale analog computing and demonstrating the potential of swarming active matter for nonlinear information processing.

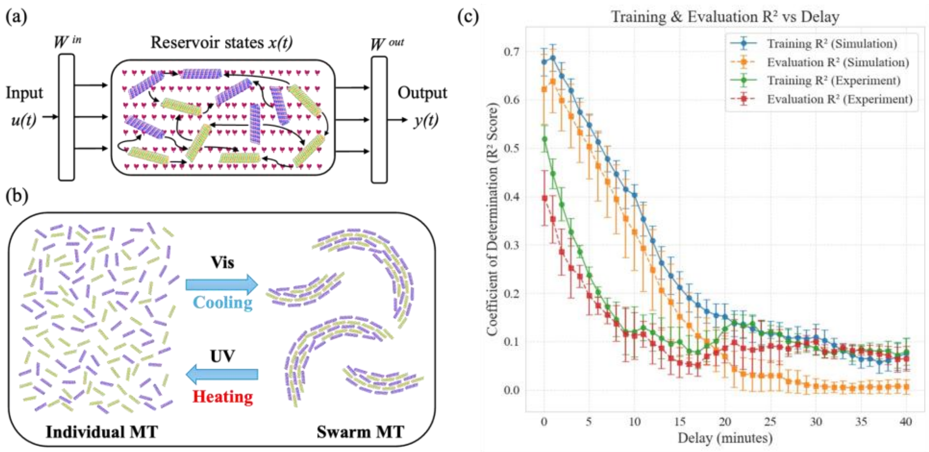

Fig. 1. (a) Schematic of PRC realized by MT swarm. (b) Temperature and UV signals modulate MT swarm, inducing transitions between collective and individual states. (c) Memory capacity of the system, evaluated by linear regression.

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Microscopic theory for the financial price formation in the presence of order-splitting traders

Kanazawa Group Yuki Sato

Abstract Recently, the availability of high-quality data with traders' identifiers has enabled us to develop a microscopic model of the financial market without heuristics. Utilising a high-quality dataset provided by the Japan Exchange Group Inc., the manager of Tokyo Stock Exchange, we developed a microscopic theoretical model of institutional trade's practical behaviour, called order splitting trading. In this presentation, we would like to provide theoretical insight into how the institutional traders' microscopic dynamics influence macroscopic financial price formation by solving the theoretical model..

Recent advances in information technologies enable us to access high-quality and high-resolution datasets even in social science [1]. Particularly in the finance field, some researchers became able to access complete event record data with trader identifiers. Such a high-quality dataset enabled us to understand macroscopic statistical laws in the financial market from microscopic dynamics without heuristics (see Fig. 1).

Fig. 1. The hierarchical structure of the financial market. Investors reveal their supply and demand using their orders, dynamically forming the mesoscopic limit order book (LOB). The resulting movement of the LOB's center, called mid-price, defines the trajectory of macroscopic financial prices.

In this research, let us focus on the relationships between the financial price formation and the institutional trader's practical behaviour called order splitting [1-3]. When investors buy/sell large amounts of stocks (called metaorders), institutional trader practically split their metaorders into a long sequence of tiny orders. This practical behaviour is called order splitting, and it is known that order-splitting behaviour causes the predictability in the macroscopic buy-sell market order flow [1]. Since buy (sell) market orders generally push the price up (down) on average, the presence of order-splitting traders would intuitively suggest that future financial prices should be predictable (or super-diffusive). Nevertheless, actual financial price dynamics obey Brownian motion, meaning future price prediction is almost impossible.

Resolving these paradoxical relationships, we developed a microscopic theoretical model of institutional traders incorporating empirical impulse response relationships of the financial prices called price impact [1-5]. We extended a plausible theoretical model of order-splitting behaviour called the Lillo-Mike-Farmer model by incorporating the square-root response of the financial prices. By solving our microscopic theoretical model, we found that the non-linear response plays a major role in resolving this paradox. In this presentation, we would like to report the role of the order-splitting traders in the financial price formation by solving our microscopic theoretical model.

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Nonlinear responses in exotic quantum states: topological superconducting states and intervalley coherent states

Condensed Matter Theory Group　　Hiroto Tanaka

Abstract Quantum condensed matters exhibit remarkable properties in response phenomena. Here, we focus on nonlinear responses in topological superconducting states and intervalley coherent states. In this presentation, we will show that characteristic nonlinear response phenomena emerge in the exotic quantum states. Nonlinear response measurements can yield rich information.

Quantum condensed matter is an attractive platform for exotic response phenomena. One of the most famous phenomena is the Meissner effect in superconductors (SCs). In addition, nonlinear optics has revealed novel phenomena in SCs because nonlinear optical processes can activate degrees of freedom that are inactive in linear optical processes [1]. Recently, the valley gauge symmetry broken states, namely intervalley coherent (IVC) states, have been reported in graphene systems [2]. It is also desired to explore novel response phenomena in the IVC states.

Our studies focus on nonlinear responses in topological SCs and IVC states. In this presentation, we will show that nonlinear response measurements can be a powerful tool to characterize these exotic states.

1. Nonlinear optical responses in topological SCs [3, 4]

Intensive research has revealed intriguing optical responses in topological materials. In this study, we investigate the second-order nonlinear optical responses in topological SCs [3, 4]. We consider s-wave SCs with a Rashba spin-orbit coupling and a magnetic field, one of the platforms of class D topological superconductivity [5]. When the magnetic field is enlarged, the transition to the topological superconducting state occurs at the critical magnetic field. Our numerical results show that the sign of the nonlinear optical conductivity reverses at the topological transition. It implies that the nonlinear optical measurement can be a bulk probe of topological SCs.

We also focus on the effects of collective excitation modes on nonlinear optical responses in the topological SCs [4]. Our main results show that the Higgs modes enhance the nonlinear responses when the Fermi level is close to the Dirac point. The enhancement is due to the multiband effects characterized by the interband pairing. In topological materials, nonlinear optics has a close relation to the quantum geometries. We also discuss the interplay between collective mode excitations and quantum geometry in the response phenomena.

2. Surface acoustic wave-driven valley current generations in the IVC states [6]

Surface acoustic waves (SAWs) are mechanical vibrations that propagate within the surface of the elastic media. The SAWs induce spatio-temporal modulations of the two-dimensional materials placed on the elastic medium. Specifically in honeycomb systems, the spatial modulations are approximately incorporated into the Hamiltonian as an external valley gauge field, namely a pseudogauge field. The SAWs generate spatio-temporally uniform valley currents via nonlinear response phenomena. In this study, we demonstrate that the IVC order leads to anomalous contributions of SAW-driven valley current generations. The anomalous contributions manifest a characteristic power law in the frequency dependence. The SAW-driven nonlinear response phenomena characterize the IVC states.

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Microscopic Theory of Transport Phenomena in the Long-range Interacting Spin Systems

Saito Group Hideaki Nishikawa

Abstract We construct the theoretical framework of energy and spin diffusion in long-range interacting spin systems. We consider the several prototypical spin systems. We show that in one dimension, there exists the transition from normal to anomalous diffusion, and in higher dimensions, normal diffusion is always exhibited as long as in the extensive regime.

Long-range interactions are ubiquitous, exemplified by gravity, the Coulomb interaction, and the dipole interaction. Here, "long-range" means that the potential follows a power-law form $V(r) \propto r^{-\alpha}$ with the distance r between the sites. Recent experimental advancements have remarkably enabled precise control over the interaction regime and the power-law exponent α. Notable examples include Rydberg atoms, cold atomic, and trapped ionic systems. These platforms not only open pathways for quantum information processing but also serve as versatile laboratories for exploring fundamental phenomena such as thermalization, information propagation, and beyond. Long-range interactions give rise to distinctive phenomena that are absent in systems governed solely by short-range interactions, from static to dynamical aspects. As important dynamical properties, energy or spin propagation should be a crucial subject in the spin systems. We focus on spin models, motivated by their direct relevance to the experimental systems mentioned above. However, thus far, the impact of long-range interaction on energy transport in spin systems have not been systematically investigated. On the other hand, the effect of long-range interaction on spin transport has been numerically and phenomenologically studied [1], but so far, a rigorous theoretical foundation has not existed.

The primary aim of this thesis is to understand the general properties of energy and spin diffusion in spin systems with long-range interactions. We address the following questions: Is there a transition of normal and anomalous diffusion of energy and spin by changing the exponent α ? If so, what is the universal mechanism and systematic method to analyze the class of energy and spin diffusion?

Firstly, we investigate energy diffusion in long-range interacting spin systems. We consider prototypical spin systems, the transverse Ising model, and the XYZ model in the D-dimensional lattice with a finite exponent $\alpha > D$ which guarantees the thermodynamic extensivity. In one dimension, both normal and anomalous diffusion are observed, where the anomalous diffusion is attributed to anomalous enhancement of the amplitude of the equilibrium current correlation. We prove the power-law clustering property of arbitrary orders of joint cumulants in general dimensions. Applying this theorem to equal-time current correlations, we further prove several theorems leading to the statement that the sufficient condition for normal diffusion in one dimension is $\alpha > 3/2$ regardless of the models. The fluctuating hydrodynamics approach consistently explains Levy diffusion for $\alpha < 3/2$, which implies the condition is optimal. In higher dimensions of $D \geq 2$, normal diffusion is indicated as long as $\alpha > D$ [2]. Next, we study spin diffusion in long-range interacting XXZ model, with a power-law exponent $\alpha > D$. We obtain the same scaling behavior for spin diffusion, both in one dimension and higher dimensions [3]. Moreover, we also investigate energy and spin diffusion in the same model above, with a power-law exponent $\alpha < D$ and Kac factor. We reveal that in one dimension, energy and spin diffusion always exhibit Levy diffusion, and in higher dimension, exhibits normal diffusion. [3] We expect this theoretical framework is broadly applicable to transport phenomena in a wide class of long-range interacting systems.

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Nonreciprocal Transport in Helical Superconducting Thin Films

Condensed Matter Theory Group Naratip Nunchot

Abstract Critical currents of a superconductor can be nonreciprocal due to certain broken symmetries at the microscopic level. This dissertation explores how dimensionality, disorder, and various interactions influence the nonreciprocal transport, paving the way for the creation of an ideal low-energy diode.

Nonreciprocal properties of matter refer to the properties in which a physical quality is unequal in one direction compared to its opposite direction. Recently, the phenomenon in which the critical currents of a superconductor (SC) become nonreciprocal, known as the *superconducting diode (SD) effect* [1], has attracted much interest. From the fundamental view, it is striking that the SD effect may arise from symmetry breaking at the *microscopic level*, which can be reflected by the depairing mechanism of Cooper pairs. The SD effect that occurs in this way is called the *intrinsic SD effect* [2]. In the applied view, the novel diode, which exhibits zero resistance when current flows in specific directions, may be a promising device for reducing the heat loss in electrical circuits.

A two-dimensional (2D) superconductor coupling with the Rashba spin-orbit interaction and in-plane Zeeman magnetic field serves as a canonical model for the theoretical study of the intrinsic SD effect. The assumption that the SC state for a given current is the helical state, which is a momentum-carrying Cooper pair state, is often imposed to investigate the effect quantitatively. In realistic materials, these 2D systems can be considered thin films, where the current flowing through them is approximately uniform if the film thickness is sufficiently thin. The intrinsic SD effect in these conventional systems can occur only if the applied magnetic field is perpendicular to the current. In that case, the SC vortices can invade the sample and be driven by current, causing Ohm's dissipation. Therefore, we must have a thinner film. However, we then encounter another problem: when the film becomes ultrathin, the properties of the system can change critically by the Berezinskii-Kosterlitz-Thouless (BKT) transition, which is the true SC transition of ideal 2D superconductors. Moreover, the Anderson localization due to impurity disorder also becomes remarkable. This can significantly alter the properties of a superconductor by cooperating with electron-electron (e-e) interactions. In this dissertation, I have dealt with these topics as follows:

(i) Chiral superconducting diode effect by Dzyaloshinsky-Moriya interaction [3]

If the intrinsic SD effect can occur even when the applied magnetic field is parallel to the current, the motion of SC vortices should be suppressed. In this work, we demonstrated that this novel SD effect can be realized in superconductors coupled with the Dzyaloshinsky-Moriya interaction and an in-plane Zeeman magnetic field.

(ii) Nonlinear diode effect and BKT transition in ideal 2D noncentrosymmetric superconductors [4]

In ideal 2D superconductors, the resistivity becomes zero only when there is no current. This challenges the concept of the critical current of a superconductor. In this work, we studied a 2D Rashba superconductor to examine this problem. We found that the voltage-current characteristics can become nonreciprocal, and a crucial role of gap amplitude fluctuation in superfluid density, which also contributes to transport properties.

(iii) Superconducting diode effect in weak localization regime [5]

The critical temperature of a conventional superconductor can be largely lowered by the Coulomb interaction (or the singlet e-e interaction). In this study, we developed a theory using the Keldysh functional formalism to describe the SD effect in a dirty Rashba superconductor incorporating the localization correction due to Coulomb interaction and disorder. We found a crucial role of this correction on the SD effect in the high-field regime.

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Discreteness-induced spatial chaos and noise-induced order in a stochastic reaction-diffusion system

Statistical Physics - Dynamics Group   Yusuke Yanagisawa

Abstract By analyzing a lattice-based stochastic reaction-diffusion model, we find a new phenomenon. In the deterministic limit, the model (zero-noise dynamics) yields stationary solutions that are aperiodic. In contrast, the steady state of the stochastic model is shown to converge to a periodic pattern as the noise intensity tends to zero.

Reaction-diffusion systems address coupled processes of chemical reaction and diffusion, leading to the emergence of self-organized patterns. The most famous example is a Turing pattern. A variety of spatial orders observed in macroscopic systems — ranging from developmental processes to vegetation in ecosystems — have been interpreted based on Turing patterns. Since Turing's seminal work [1], most studies have relied on deterministic partial differential equations (PDEs). This approach assumes a continuum description, namely that patterns can be represented by spatially coarse-grained concentration fields. As a result, traditional theory has primarily focused on pattern formation at macroscopic scales.

Recently, however, Turing-like patterns have been observed at microscopic scales where the continuum description breaks down. One example is the pattern formation of atomic-scale quantum wires deposited on a substrate [2]. It is far from obvious that Turing patterns seen in macroscopic systems would persist across scales to microscopic systems. Unlike macroscopic systems, fluctuations and the discreteness of patterns play a dominant role in microscopic systems, and the pattern formation mechanisms cannot be fully captured by conventional deterministic PDEs. How fluctuations and discreteness influence the emergence of patterns in microscopic systems remains to be elucidated.

In this work, we study a lattice-based stochastic reaction-diffusion model and analyze the Turing patterns. By comparing the stochastic model with its corresponding deterministic model, we clarify how fluctuations affect pattern formation [3]. We focus on the regime where the pattern wavelength is comparable to the lattice constant. In the deterministic limit, the model (zero-noise dynamics) yields stationary solutions that exhibit spatial chaos (Fig. 1). This implies that, even when the Turing mechanism is present, spatial discreteness prevents stationary solutions from becoming spatially periodic. In contrast, the steady state of the stochastic model is shown to converge to a periodic pattern as the noise intensity tends to zero. This indicates that weak noise orders the spatial chaos.

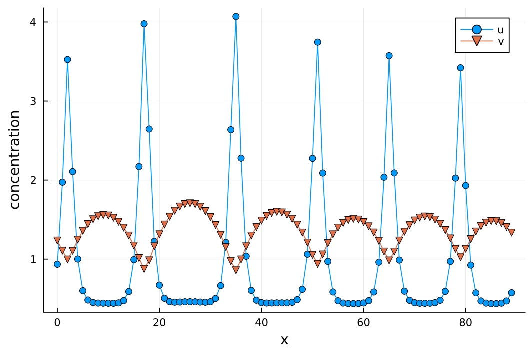

Fig. 1. A spatially chaotic stationary solution of the deterministic model.

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Unifying renormalized and bare viscosity in two-dimensional molecular dynamics simulations

Statistical Physics and Dynamics Group Kazuma Yokota

Abstract We study two-dimensional fluids, bridging renormalized and bare viscosity via a wavenumber-dependent viscosity defined through a finite-wavevector extension of the Green–Kubo formula. Molecular dynamics simulations reveal a small-wavenumber divergence matching renormalized viscosity and a large-wavenumber plateau yielding bare viscosity, thereby linking mesoscopic and macroscopic transport.

Although the motion of microscopic particles is highly complex, the macroscopic behavior of a system can often be described by the time evolution of a few macroscopic variables. Hydrodynamics is one of the most successful theoretical frameworks for describing such macroscopic behavior. However, in systems of two or fewer dimensions, transport coefficients such as thermal conductivity exhibit size-dependent divergences. This anomaly stems from thermal fluctuations. Thus, an appropriate framework for low-dimensional systems must incorporate their effects.

Fluctuating hydrodynamics [1] provides such a framework by adding thermal noise to the hydrodynamic equations. The transport coefficients in fluctuating hydrodynamics are called bare transport coefficients, and they are generally distinct from the macroscopic transport coefficients observed in experiments or numerical simulations, which are referred to as renormalized transport coefficients. Because the bare transport coefficients govern the behavior of fluctuating hydrodynamics, determining their values is essential for quantitatively predicting transport properties in low-dimensional systems where standard hydrodynamics breaks down.

Given that fluids are composed of microscopic particles, determining bare transport coefficients from a microscopic particle description is a significant challenge. In this context, a formula for the bare transport coefficients was proposed in [2], based on a projection operator method. Although this formula is formally correct under several technical assumptions, numerical implementation of the projection-operator method is generally difficult. To bypass this difficulty, a numerically tractable formula combining coarse-graining with the projection operator method was developed [3], though confirmation of its validity remains open. More recently, a practically useful estimation method based on nonequilibrium measurements near boundaries has been proposed [4], but it currently lacks a comprehensive theoretical foundation and requires the simultaneous determination of the ultraviolet cutoff a_{uv}. Despite these advances, a systematic framework that unifies bare and renormalized transport coefficients starting from a microscopic particle description is still missing.

In this presentation, we address this gap by focusing on the viscosity in two-dimensional fluids. Our central idea is to bridge the renormalized viscosity $\eta_{\mathrm{R}}(L)$ and bare viscosity η_0 by introducing a wavenumber-dependent viscosity $\eta_*(k)$, where $k = |\boldsymbol{k}|$ is the magnitude of the wavevector. As a finite-wavevector extension of the Green–Kubo formula, we define $\eta_*(k)$ from the equilibrium correlation of time-averaged Fourier components of the fine-grained shear-stress field. Molecular dynamics simulations of two-dimensional fluids show that $\eta_*(k)$ exhibits a divergence at small k mirroring that of $\eta_{\mathrm{R}}(L)$ and a plateau at large k corresponding to η_0. From the behavior of $\eta_*(k)$, we determine η_0 and a_{uv}. In this way, the wavenumber-dependent viscosity $\eta_*(k)$ links mesoscopic and macroscopic transport behavior. This presentation is based on [5].

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