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要旨集

２０２４年１１月２１日(木)、２２日(金)

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２０２４年１１月２１日（木）９：００～　開始

目　　次

２０２４年１１月２２日（金）９：００～　開始

１２：１０～１３：１０　休憩

１４：４０～１４：５０　休憩

Chiral Boundary Current Along Chiral Domain Walls in Superfluid ^{3}He-A

Ultra Low Temperature Physics Group　　Yuto Ikegai

Abstract Along the boundaries of chiral domains in superfluid ^{3}He-A, spontaneous orbital supercurrents are expected. Utilizing their interaction with an externally applied superflow, we have successfully demonstrated the existence of orbital supercurrents along the chiral domain walls between these domains and determined the direction of the chiral axis in adjacent domains.

Recently, the topological properties of chiral superconductors and chiral superfluids have been actively studied. Among these, superfluid ^{3}He-A stands out as an ideal system for investigating the fundamental properties of chiral superfluids. This is because we can control the shape of space and the surface conditions of superfluids, and we can obtain clear experimental results without impurities. In the ^{3}He-A phase, the chiral axis is represented by the $\hat{\boldsymbol{l}}$-vector, and the direction of the angular momentum of Cooper pairs aligns with it. A region where the chiral axes are uniformly aligned is called a "chiral domain." It is crucial for investigating the properties of the chiral superfluid to know where the chiral domains are and what their shape is. Kasai et al. used MRI to successfully visualize the spatial distribution of chiral domains in ^{3}He-A confined between parallel plates 100 μm apart [1], a significant step toward exploring their topological properties. One such property is the boundary current expected to flow around these chiral domains. This current reflects the angular momentum of the Cooper pairs and appears as the orbital supercurrent at the domain boundaries. We have demonstrated the existence of this orbital supercurrent by utilizing its interaction with an externally applied superflow. Additionally, we clarified the direction of the orbital supercurrent and the direction of the chiral axis within adjacent chiral domains.

In the parallel plate configuration, chiral domains are formed with the $\hat{\boldsymbol{l}}$ oriented perpendicular to the plates, as shown in Fig. 1. When multiple domains with different $\hat{\boldsymbol{l}}$ directions coexist, domain wall structures form between them. Orbital supercurrents flow around each chiral domain, and these currents are also expected to exist along the domain walls. The orbital supercurrent interacts with an externally applied superflow, tilting the domain walls from the vertical direction toward the direction shown in Fig. 1. This tilting effect arises from the interaction with the anisotropic component of the orbital supercurrent $\boldsymbol{g}_{s,orb2}$ and the external superflow $\boldsymbol{v}_s$, through a term $\boldsymbol{g}_{s,orb2}\cdot\boldsymbol{v}_s$ in the gradient energy. We applied an external superflow to the chiral domains confined between parallel plates spaced 100 μm apart and confirmed through MRI that this interaction caused the domain walls to tilt. Fig. 2 shows an MRI image projected in the direction perpendicular to the plates, where the tilted domain walls appear as stripes. From the direction of this tilt, we determined the direction of the orbital supercurrent and the direction of the $\hat{\boldsymbol{l}}$ in each chiral domain.

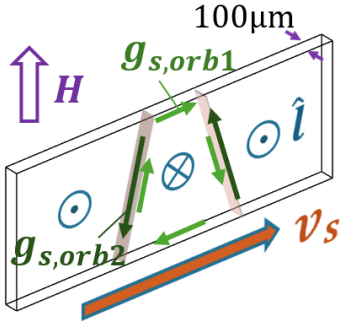

Fig. 1. Illustration of orbital supercurrent along boundary of chiral domains and tilted domain walls

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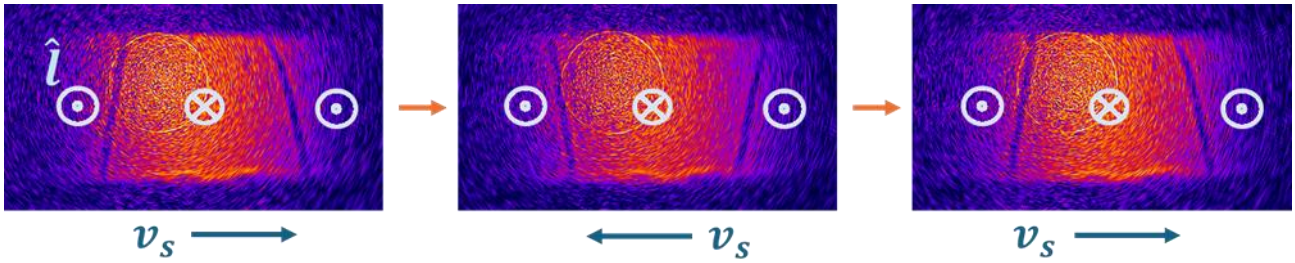

Fig. 2. MRI image of tilted chiral domain walls by externally applied superflow

Definition of current in non-Hermitian quantum mechanics

YITP　Hiroto Oka

Abstract　Quantum mechanics in systems without hermiticity is a hot topic today. In those systems, the equation of continuity, which is essential to the definition of the current, does not always hold even when probability is conserved. We investigate a model non-Hermitian quantum system interacting with the Maxwell electromagnetic field and propose a new definition of the current which satisfies the equation of continuity.

Non-Hermitian quantum systems is a field which is studied actively these days. In quantum mechanics, Hamiltonian is normally Hermitian. If quantum systems interact with their surroundings and the surroundings are measured, however, there are cases in which the Hamiltonian is not Hermitian effectively [1]. Those cases are called non-Hermitian quantum systems.

In this research, we studied the definition of the current in non-Hermitian quantum system. In the usual Hermitian quantum systems, the current is defined from through the equation of continuity, which describes the probability conservation. In non-Hermitian quantum systems, on the other hand, the equation of continuity does not always hold due to non-Hermiticity even though probability is conserved. This is because the non-Hermiticity comes from backaction from measurements of the surroundings. To solve this problem, I propose a new definition the electrical current which satisfies the equation of continuity even in non-Hermitian quantum mechanics. In the previous work on this problem, the current which flows out of the system has been considered [2] to solve this problem. In contrast, we focus on the current which flows inside of the system in this work.

To demonstrate our approach, we consider non-Hermitian quantum systems (for example, electron systems) coupled to the electromagnetic field interact. And I tried to define new current by researching how Maxwell equations change in those systems with non-Hermitian time evolution.

As a result, the Maxwell equations are modified to have terms coming from non-Hermiticity. From those equations, a new current which has physical meanings and satisfies the equation of continuity can be defined. Furthermore, we use the current defined this way to calculate the linear response in specific non-Hermitian quantum systems and compare the results with those based on the conventional current.

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Branching structure in slippery type colloidal aggregation

Phase transition dynamics group, Koichi Hirata

Abstract We numerically investigated the aggregation behavior of slippery-type colloids and the resulting gel network using a slippery diffusion-limited cluster aggregation (DLCA) model. The cluster or gel structures consist of strands formed by numerous particles. Our results reveal two distinct pathways for forming a strand network, depending on the particle concentration.

When colloidal particles in a solvent interact via strong attraction, a macroscopic cluster with elasticity, known as a colloidal gel, is formed. This material is ubiquitous in nature and in various industries. While its viscoelasticity originates from load-bearing paths within the gel network, the precise mechanisms underlying its elastic properties—such as the dependence of elastic constants on concentration—remain unresolved.

The diffusion-limited cluster aggregation (DLCA) model [1] is a classic model for colloidal aggregation. Here, particles are initially uniformly distributed and undergo Brownian motion, forming irreversible bonds with complete bending rigidity upon contact, resulting in rigid clusters. Experimentally, if attractive forces are strong and short-ranged, contacting particles interact through surface asperities, generating bending rigidity [2,3]. Such structures are well captured by the DLCA model. However, when attraction is not so short-ranged or surfaces are smooth, the resulting gel structure shows locally dense strands of particles [4]. The slippery DLCA model [5] is similar to DLCA but lacks bending rigidity, effectively reproducing these dense strand structures, as shown in Fig. 1(a).

We believe that characterizing this gel structure as a branching network of strands is essential for understanding its elasticity, also emphasized in several studies [6,7]. Using the slippery DLCA model, we numerically investigated the formation dynamics of this branching structure at various particle concentrations. Our findings revealed two distinct formation pathways [8]: below a volume fraction (ϕ) of 8%, significant deformation occurs in smaller clusters before larger, percolated clusters are established, leading to the collapse of branching sections, as illustrated in Fig. 1(b). Above 8%, percolated clusters with a homogeneous, fine network structure are initially formed, followed by local deformations that elongate strands and coarsen the branching regions, as shown in Fig. 1(c).

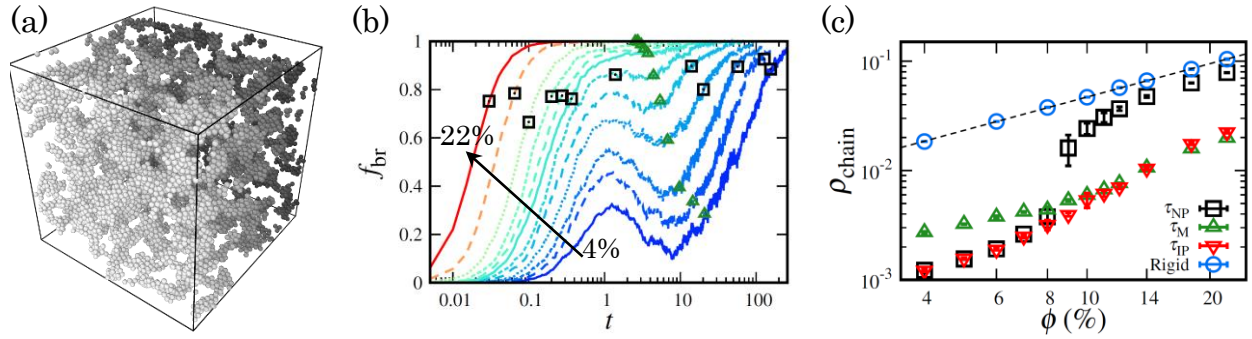

Fig. 1. (a) Snapshot of $\phi = 8\%$ slippery DLCA gel. (b)Time evolution of fraction of particles included in clusters with branching part $f_{\rm br}$. From bottom to top, volume fraction changes as $\phi = 4,5,6,7,8\%$, and $\phi \geq 9\%$. $\phi \leq 8\%$ systems show decreasing behavior at intermediate time. (c)The number density of chain parts (strands) at various time. $\tau_{\rm NP}$ is percolation time, $\tau_{\rm M}$ is time at which average number of bonds per particle becomes six, and $\tau_{\rm IP}$ is percolation of particles with six bonds. Rigid means the value of original DLCA gel, characterized by the power-law behavior.

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Theoretical study on spin transport phenomena in novel nonequilibrium states

Condensed Matter Theory Group Ryotaro Sano

Abstract Recent remarkable advances in experimental techniques are opening the door to novel quantum regimes, which were previously out of reach. Motivated by these experiments, we aim to access novel nonequilibrium states from a spintronic viewpoint. In this study, we reveal various transport phenomena and propose experimental methods to detect them.

Quantum transport has attracted a profound growth of interest owing to its fundamental importance and many applications. Recent significant developments in experimental techniques have further boosted the study of quantum transport and revealed various novel quantum regimes, which were previously out of reach. In this work, we mainly focus on the hydrodynamic regime, 2D magnetism, and chirality-induced spin selectivity from a spintronic viewpoint and propose methods to access their nonequilibrium states.

1. Hydrodynamic regime in ferromagnetic insulators and breakdown of the Wiedemann-Franz law [1]

In ultrapure systems, interactions between particles drastically affect the transport properties, resulting in an emergent nonequilibrium states inherent in the so-called hydrodynamic regime. Recent experiments have shown an indication of a hydrodynamic magnon behavior in ultrapure ferromagnetic insulators [2]; however, its direct observation is still lacking. Here, we derive a set of coupled hydrodynamic equations and study the thermal and spin conductivities for such a magnon fluid. We reveal the drastic breakdown of the magnonic Wiedemann-Franz law as a hallmark of the hydrodynamics regime, which will become key evidence for the experimental realization of an emergent hydrodynamic magnon behavior.

2. Interplay between surface acoustic waves and 2D van der Waals antiferromagnets [3]

The recently discovered van der Waals antiferromagnets have suffered from the lack of a comprehensive method to study their magnetic properties due to the 2D nature [4]. Here, we propose an ac intrinsic magnon spin Hall current driven by surface acoustic waves as a novel probe for such antiferromagnets. Our results pave the way towards mechanical detection and manipulation of the magnetic order in two-dimensional antiferromagnets. Furthermore, they will overcome the difficulties with weak magnetic responses inherent in the use of antiferromagnets and hence provide a building block for future antiferromagnetic spintronics.

3. Chiral phonon-assisted variable-range hopping along the DNA double helix [5]

Recent transport experiments on chiral materials indicate the strong correlation between their structural chirality and electron spin, which is the so-called chirality-induced spin selectivity (CISS) [6]. However, the underlying mechanisms of the CISS effect are still long-standing mystery. We here present a variable-range hopping model to describe the chirality-induced spin selectivity along the DNA double helix. In this model, DNA is considered as a one-dimensional disordered system, where electrons are transported by chiral phonon-assisted hopping between localized states. Owing to the coupling between the electron spin and the chiral phonons, electric toroidal monopole appears in the charge-to-spin conversion as a manifestation of true chirality. Our model explains the formation of anti-parallel spin pair and the temperature dependence of the CISS effect observed in experiments.

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Magnetoelectric correlations in noncentrosymmetric superconductors

Condensed Matter Theory Group Koki Shinada

Abstract Spatial inversion symmetry breaking enriches material phases and physical phenomena. Here, we focus on a magnetoelectric correlation (the Edelstein effect) in superconductors, proposing an observation method through optical activity and discussing its relation to the center-of-mass momentum of Cooper pairs.

Breaking of spatial inversion symmetry leads to rich material phases and response phenomena. This effect is mainly introduced through spin-orbit coupling, which determines the spin structure in momentum space of a ground state. Consequently, a strong spin-momentum (in other words, magneto-electric) correlation arises, establishing diverse fields such as spintronics, multiferroics, and topological material science. This magnetoelectric correlation is also strongly manifested in superconductors, giving rise to parity-mixed superconductivity, helical superconductivity, and topological superconductivity. While various candidate materials have been proposed for such exotic states, definitive detection methods are keenly anticipated.

In this presentation, we will focus on the superconducting Edelstein effect, one of the magnetoelectric phenomena. We will give an optical method for the precise measurement of this effect. In addition, we will show that this effect can serve as a powerful and direct detection method for exotic superconductors.

1. Unique properties of the optical activity in noncentrosymmetric superconductors: Sum rule, missing area, and relation with the superconducting Edelstein effect

The superconducting Edelstein effect is a type of cross-correlation phenomena inducing a magnetization via a supercurrent. This response coefficient contains essential information charactering superconductors without inversion center; however, no measurement has been reported since its proposal [1]. Therefore, we have proposed a precise measurement method for the response coefficient using the optical activity [2]. The optical activity is observed in the form of circular dichroism and optical rotation in , e.g., chiral materials. We have derived a unique sum rule for noncentrosymmetric superconductors, showing that a measurable *missing area* is equivalent to the response coefficient. This sum rule is an extension of the Ferrell-Glover-Tinkham sum rule measuring the superfluid weight using the optical conductivity [3,4].

2. Thermodynamic relations for the Cooper pair's momentum in helical superconductors

We have proposed two thermodynamic relations for the exact measurement of the center-of-mass (COM) of Cooper pairs in helical superconductors [5]. The first relation is related to the superconducting Edelstein effect, giving a differential formula determining how the COM momentum should change if we change a magnetic field. The second relation is related to a first-order phase transition, where the finite COM momentum jumps. This relation is an analogy of the Clausius–Clapeyron equation known in the liquid-gas transition. These results give a strong and direct evidence of the helical superconductivity.

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Unconventional pressure dependence of the superconductivity in the Dirac line-nodal material $CaSb_2$

Quantum Materials Laboratory　Hidemitsu Takahashi

Abstract We investigated the origin of unusual pressure dependence of the superconducting transition temperature T_c of the Dirac line-nodal material $CaSb_2$. We performed ^{123}Sb-nuclear quadrupole resonance and X-ray diffraction measurements under pressure, and revealed that the anomalous phononic properties are likely to be the key for nonmonotonic T_c response against pressure.

Recently, topological superconductivity has become a subject of intense research in condensed matter physics. Superconductivity in a line-nodal material, which has topologically protected band crossings along curves in the Brilloin zone, is one of the good candidates for bulk topological superconductivity. $CaSb_2$ is a superconductor and predicted to be a line-nodal material from theoretical calculations [1, 2]. The expected band structure is experimentally supported [3, 4]. $CaSb_2$ is especially suitable for investigating the superconductivity in the line-nodal material because its line nodes are protected by nonsymmorphic crystalline symmetry and robust against the spin-orbit coupling.

We revealed its conventional *s*-wave superconducting (SC) behavior at ambient pressure by $^{121/123}$Sb-nuclear quadrupole resonance (NQR) measurements [5]. However, the SC transition temperature T_c shows a peak under pressure [Fig. 1 (a)] [6], indicating the unconventional SC character. The aim of this study is to reveal the origin of this peak. According to the BCS theory, information on the electronic density of states (DOS) and crystal lattice are required.

First, we performed ^{123}Sb-NQR measurements under pressure up to 2.08 GPa to examine the pressure dependence of DOS because it usually dominates the pressure dependence of T_c in BCS superconductors [7]. The constant value of nuclear-spin lattice relaxation rate $1/T_1$ divided by temperature was insensitive to pressure, evidencing pressure independent DOS up to 2.08 GPa [Fig. 1 (b)].

Second, we investigated the crystal structure under pressure by X-ray diffraction measurements up to 9. 71 GPa. At about 3 GPa where T_c reaches the maximum, subtle anomalies were observed in the pressure dependence of lattice parameters, while the crystal symmetry did not change [Fig. 1 (c)]. This result suggests the existence of a first-order structural transition affecting the SC state. Especially, the unusual phononic properties causing anomalous behavior in *V*, are expected to be important for determining T_c under pressure.

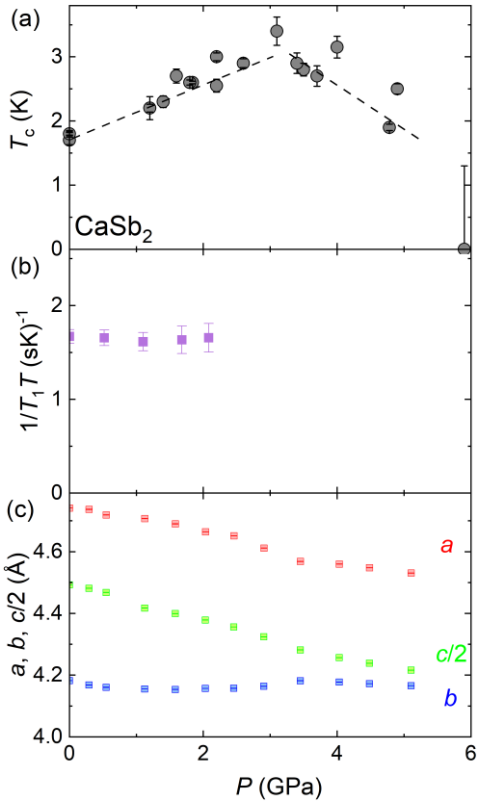

Fig. 1: Pressure dependence of (a) T_c, (b) $1/T_1T$, and (c) the lengths of crystal axes.

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Quantum Geometry and Superconductivity

Condensed Matter Theory Group Taisei Kitamura

Abstract Quantum geometry refers to the geometric properties of Bloch wave function in wave number space and attracts much attention in modern condensed matter physics. In this work, we show that the quantum geometry induces various exotic superconductivity. Our theory provides a novel strategy to realize such exotic superconductivity.

Quantum geometry, which is the geometric properties of the Bloch wave function, is characterized by a quantum geometric tensor whose real and imaginary parts are quantum metric and Berry curvature, respectively [1]. Recently, such quantum geometric quantities have been revealed to appear in various physical phenomena. In superconductivity, the quantum geometry is known to appear in the superfluid weight. Since quantum metric gives superfluid weight in flat-band systems, quantum geometry of superconductivity has been mainly studied in the flat-band system [2].

However, the quantum geometric effect on the superconductivity is not limited to the flat-band system and various superconducting phenomena where quantum geometry plays an important role may remain not to be found. In this work, we find three different exotic superconductivity which is induced by quantum geometry, (i) Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) superconductivity [3], (ii) anapole superconductivity [4], (iii) spin-triplet superconductivity [5]. Thus, we shed light on the novel way to realize various exotic superconductivity by quantum geometry as follows.

(i) Quantum geometric effect on Fulde–Ferrell–Larkin–Ovchinnikov superconductivity [3]

While Cooper pairs of usual BCS superconductivity do not have finite momenta, FFLO superconductivity where Cooper pairs have finite momenta is known to be realized in high-magnetic field regions. Such an exotic state is induced by the negative superfluid weight due to the magnetic field. In this work, we study the quantum geometric effect on FFLO superconductivity. As a result, we found quantum-geometry-induced FFLO superconductivity.

(ii) Quantum-geometry-induced anapole superconductivity [4]

Other than the negative-superfluid mechanism of finite-momentum superconductivity, the presence of the Lifshitz invariance also ensures the finite-momentum pairing; one example is known to be anapole superconductivity. In this study, we show that quantum geometry can induce the Lifshitz invariant and, thereby, anapole superconductivity.

(iii) Quantum-geometry-induced Spin-triplet superconductivity [5]

While spin-triplet superconductivity is the platform of topological superconductivity, the candidate materials of spin-triplet superconductivity are quite rare. Also, while usually spin-triplet superconductivity is induced by ferromagnetic fluctuation, ferromagnetic fluctuation is also rare, especially in two-dimensional systems which is considered to be a reason for the lack of candidate material. In this study, we show that quantum geometry can induce ferromagnetic fluctuation even in a two-dimensional system resulting in spin-triplet superconductivity.

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Observation of ytterbium atoms in an optical lattice by quantum gas microscopy

Quantum Optics group Noritaka Kitamura

Abstract We develop an ytterbium quantum gas microscope using a solid immersion lens. We prepare a Bose Einstein condensate of ^{174}Yb atom and a Fermi degenerate gas of ^{173}Yb, and load them into a two-dimensional optical lattice. We demonstrate fluorescence imaging of Yb atoms with single site resolution.

In recent years, quantum simulations of the Hubbard model using a system of laser-cooled atomic gases in an optical lattice have attracted much interest. Quantum gas microscopy is a powerful observational tool for experiments on ultracold atom systems in optical lattices. We can directly observe individual atoms trapped in an optical lattice using an imaging system with high spatial resolution. The realization of quantum gas microscopy has led to the observation of long-range antiferromagnetic correlations in the Fermi Hubbard model [1].

Up to now quantum gas microscopes have mostly been developed with alkali atoms, Recently, quantum gas microscopy of Yb [2,3], Sr [4,5], and Er [6] atoms has also been reported. We are particularly interested in Yb atoms which have many stable isotopes, including five bosons and two fermions. In addition, Yb atoms are two-electron atoms with three metastable states, 6s6p $^3P_0$, 6s6p $^3P_2$, and $4f^{13}5d\ 6s^2$(J = 2). These features make it possible to study Hubbard model with SU(N=6) symmetry using ^{173}Yb with nuclear spin I=5/2 [7] and the two-orbital SU(N) Hubbard model in combination with the $^3P_0$ state [8].

In this study, we developed the quantum gas microscope of Yb atoms in an optical lattice. First, BEC of ^{174}Yb atoms was achieved by evaporative cooling of the atoms prepared just below a solid-immersion lens. Next, atoms were introduced into a two-dimensional optical lattice with a lattice spacing of 541 nm, and high-resolution fluorescence imaging was performed using the $^1S_0$-$^1P_1$ transition (Fig. 1). The fluorescence we observed at the lattice points is from isolated single atoms, as confirmed by histogram analysis of the fluorescence count. We also performed the experiment using a Fermi-degenerate gas of ^{173}Yb atoms and site-resolved fluorescence imaging. We have also proposed an experimental procedure of spin-resolved quantum gas microscope using the metastable $^3P_2$ states. In combination with the spin-resolved measurements, we expect to be able to clarify the SU(N) quantum magnetism with long-range spin correlations in combination with spin-resolved measurements.

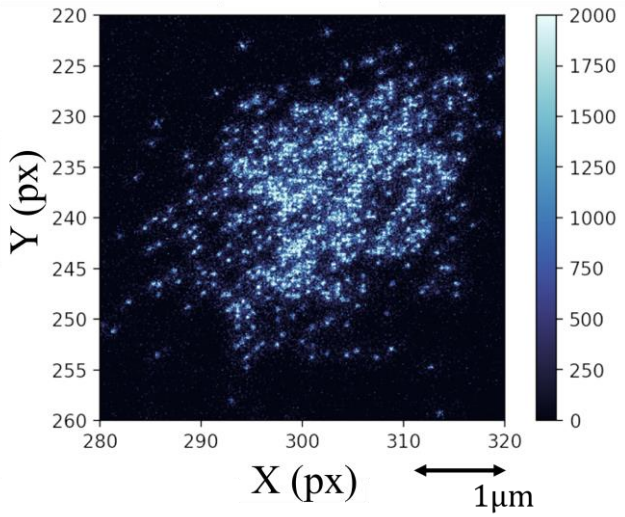

Fig. 1: Site-resolved fluorescence image of ^{174}Yb atoms in a two-dimensional optical lattice

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Dielectric screening of excitons in two-dimensional semiconductors

Solid State Spectroscopy Group Shinya Takahashi

Abstract We observed energy levels of s-series and p-series excitons in hBN-encapsulated monolayer MX_2 (M=Mo, W, X=S, Se) by sum frequency generation spectroscopy. The power-law scaling of binding energies suggested that dielectric screening of excitons can be described well by 3D-like Coulomb interaction with the dielectric constant of hBN other than 1s excitons.

Exciton (electron-hole bound pair) in monolayer transition metal dichalcogenides (1L-TMDs) is an excellent platform to study Coulomb interaction in two-dimensional materials. 1L-TMD exciton is known to have binding energy as large as a few hundred meV and a non-hydrogenic energy level structure [1]. The energy level structure of s-series excitons has been investigated by adopting encapsulation technique using hexagonal boron nitride (hBN) [2,3], which offers narrow linewidths of exciton spectral lines [4]. The energy levels were analyzed by conducting numerical calculations with the Rytova-Keldysh potential [5,6] with the dielectric constant of hBN as a tuning parameter [2,3]. Obtained dielectric constants of hBN were approximated by the high-frequency limit of the infrared dispersion [7]. On the other hand, hBN has phonon resonances with energies near the binding energies of 1L-TMD excitons and the resonances may significantly modify the exciton level structure theoretically [8]. It is an urgent topic to elucidate this effect through experiments.

Here, we observed s-series and p-series excitons in hBN-encapsulated 1L-TMDs (MoS_2, $MoSe_2$, WS_2, and WSe_2) simultaneously by sum frequency generation spectroscopy [9,10]. The degeneracy of s-series and p-series excitons is lifted by modified Coulomb potential in a thin film [11]. Therefore, the energy splitting of s-series and p-series excitons is a direct measure of different dielectric screening effects in 1L-TMDs and hBN. To analyze the experimentally obtained exciton energy level structure, we numerically calculated exciton binding energies with the Rytova-Keldysh potential. Numerical calculations with adjusted dielectric parameters of hBN and 1L-TMDs provided exciton energy levels which agreed with the experimentally obtained ones with errors of a few meV. The adjusted relative dielectric constants of hBN were found to be almost the same for four materials and approximated well by the high-frequency limit of the infrared dispersion similarly to the results in the previous studies. This suggested that the dielectric constant of hBN for excitons in 1L-TMDs are manifested by electronic contributions and negligibly little by phonons.

We examined the power-law scaling of binding energies to investigate dielectric screening effect in hBN on the exciton level structure. By using numerically obtained exciton wave functions, we calculated effective Coulomb potential energies with the adjusted dielectric constants of hBN. Binding energies and Coulomb potential energies were normalized by effective kinetic energies, which were also calculated using exciton wave functions. We found that the power-law scaling of exciton levels other than 1s can be well described by the virial theorem for the 3D hydrogen model [10,12]. On the other hand, the power-law scaling of 1s excitons deviated from the tendency of the other exciton levels. These results suggested that dielectric screening of excitons can be described well by 3D-like Coulomb interaction with the dielectric constants of hBN other than 1s excitons.

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A dual-isotope ytterbium atom array towards mid-circuit measurements

Quantum Optics Group Yuma Nakamura

Abstract We report the realization of a dual-isotope ytterbium atom array for mid-circuit measurements essential for quantum error correction. We achieved high detection fidelity of ancilla qubits with minimal decoherence of data qubits. Combined with coherent Rydberg excitation with a high-power laser we developed, this study advances the path toward fault-tolerant quantum computing.

Neutral atoms trapped in an optical tweezer array have become increasingly prominent as a platform for quantum simulation and computation [1]. The attractive features, such as the scalability of qubits [2] and flexible qubit connectivity with moving tweezers [3], facilitate realizing quantum error correction (QEC) towards fault-tolerant quantum computation. However, reading out the ancilla qubits, which are called mid-circuit measurements and essential in QEC protocols, without disrupting the data qubits is still challenging. This difficulty arises from the readout method that requires global irradiation of the probe beam, which induces heating and decoherence of atoms.

In this study, we investigate the potential of using a dual isotope ytterbium (Yb) atom array for mid-circuit measurements [4]. The dual-Yb array consists of fermionic ^{171}Yb and bosonic ^{174}Yb. The nuclear spin qubit encoded in the ground state of ^{171}Yb acts as a data qubit and offers a second-order long coherence time and MHz-order fast qubit control. On the other hand, the optical clock qubit in ^{174}Yb provides the capability of non-destructive qubit readout and, thus, is a promising candidate for ancilla qubit.

First, we succeeded in preparing a dual-Yb system in a 10×10 optical tweezer array with a 21(6) % loading probability for both isotopes while minimizing the probability of dual occupancy, where both isotopes occupy the same sites, to 0.2(7) % by optimizing the frequency of the light-assisted collision beam. From this randomly loaded atom array, we made defect-free dual-Yb arrays by moving tweezers (Fig. 1(a)), which provides the starting point for quantum computation.

Next, we quantified the influence on the coherence of the nuclear spin qubits from the imaging light for ^{174}Yb by comparing the Hahn-echo signal with and without imaging during the sequence. For 20 ms exposure to the imaging light, the coherence is maintained by 99.1(1.8) % compared to the coherence without imaging, while the ^{174}Yb detection fidelity of 0.9992 and survival probability after imaging of 0.988 is achieved (Fig. 1(b)).

In addition to these experiments, we developed a high-power ultraviolet laser (wavelength of 325 nm, output power of 800 mW) [5]. Using this laser, we observed Rabi oscillation between the metastable $(6s6p)^3P_2$ and a $(6s71s)^3S_1$ Rydberg states with a Rabi frequency of $2\pi\times2.13(3)$ MHz, which is a foundational step to high-fidelity two-qubit gates mediating the Rydberg interactions. By combining the dual-Yb atom array's capabilities with fast Rydberg excitation for two-qubit gates, these results advance the development of QEC and fault-tolerant quantum computing.

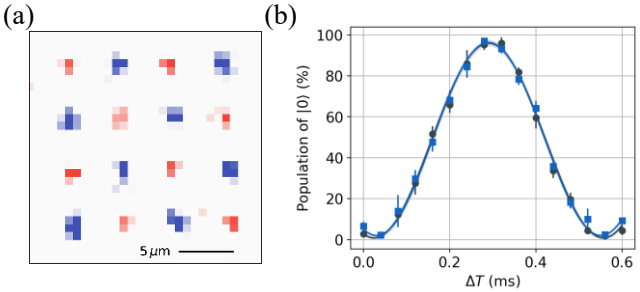

Fig.1 Dual-Yb experiments. (a) Defect-free 4×4 dual-Yb array. The red and blue points represent ^{171}Yb and ^{174}Yb respectively. (b) Hahn-echo signals of data qubits with (blue) and without (black) imaging of ancilla qubits.

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Quantum simulation of few-body and many-body phenomena in an optical lattice: effective multi-body force and nonequilibrium dynamics in isolated and open systems

Quantum Optics Group Kantaro Honda

Abstract We performed quantum simulation experiments of few-body and many-body phenomena in an optical lattice. In particular, we studied (1) effective multi-body forces in a few-body system, (2) sign reversal behavior of the magnetic correlation under the dissipation, and (3) nonergodic behavior after sudden quench in a one-dimensional system.

In 1981, R. P. Feynman proposed the concept of the 'Quantum simulation' [1], namely, simulating the quantum system of interest with another highly controllable quantum system. Now, more than 40 years after that proposal, we have witnessed the remarkable progress of artificial quantum systems, such as ultracold gases, Rydberg atom arrays, trapped ions and superconducting qubits, as ideal platforms of the quantum simulation. Among them, ultracold gases in an optical lattice, where the celebrated Hubbard model can be realized, have been used extensively in particular to elucidate the complex behavior of strongly correlated quantum many-body systems [2]. In our work, we study novel quantum few-body and many-body phenomena, utilizing an optical lattice system with trapped ultracold ytterbium atoms as a quantum simulator, as briefly summarized below.

1. Effective multi-body forces in a quantum few-body system in a strongly interacting regime **[3]**

In quantum few-body systems, effective multi-body interactions or forces, which appear in an effective theory at low energy, has been intensively studied [4]. In this work, we extend an experimental study of multi-body forces to a strongly interacting regime beyond perturbative treatments of the interparticle interaction so far, controlling the wide range of interatomic interactions via an inter-orbital Feshbach resonance. As one important illustration of entering such a regime, we obtain a clear signature of an effective four-body force.

2. Sign reversal of the magnetic correlation in a driven-dissipative Fermi-Hubbard system **[5]**

Dissipation, which on the one hand disturbs the coherent dynamics in quantum systems, on the other hand can lead to novel phenomena [6]. In this work, we investigate the influence of the dissipation on the quantum magnetism in the Fermi-Hubbard system [7], implementing the on-site two-body loss as a dissipation in a controlled manner. In a wide range of lattice configurations over an isolated double-well lattice, we observe a ferromagnetic correlation, which is a sign-reversed one from the usual antiferromagnetic one in a closed system.

3. Nonergodic behavior after the sudden quench in a one-dimensional Bose-Hubbard system **[8]**

Thermalization of isolated quantum many-body systems has attracted considerable interest, where the nonergodic system, which do not show the thermalization, is of the major interest [9]. In this work, we study the quench dynamics starting from a period-two charge-density wave of doublons in the one-dimensional Bose-Hubbard system with no tilt potential [10]. As a signature of a nonergodic behavior in this system, we observe a slow relaxation of the atom number imbalance between the odd and the even sites.

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Unconventional finite-momentum superconductivity in trilayer transition metal dichalcogenides

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Abstract We theoretically investigate the finite-momentum superconducting state induced by the orbital effect of the magnetic field. We numerically determine the superconducting phase diagram of a minimal model of trilayer $NbSe_2$, which is one of the superconducting transition metal dichalcogenides, and predict the coexistence of finite-momentum and zero-momentum Cooper pairs.

While Cooper pairs with zero center-of-mass momentum are stabilized in conventional superconductors, Cooper pairs can have finite momentum under various conditions. For instance, Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states can be realized by the Pauli paramagnetic effect of an external magnetic field [1]. In noncentrosymmetric superconductors with Rashba spin-orbit coupling, the paramagnetic effect of an in-plane magnetic field stabilizes helical superconducting states [2].

Recently, transition metal dichalcogenides (TMDs) such as $NbSe_2$ have attracted much attention as candidates for a new class of finite-momentum superconductors called the orbital FFLO superconductors [3-6]. The in-plane paramagnetic effect is suppressed by the Ising SOC in TMDs [7], and the orbital effect of the in-plane magnetic field can stabilize the finite-momentum Cooper pairs.

In this work, we theoretically investigate the superconducting phase diagram of trilayer $NbSe_2$. We construct the trilayer tight-binding model based on the monolayer model which reproduces the low-energy band structure and Fermi surface of monolayer $NbSe_2$. We solve the Bogoliubov-de Gennes equation considering the orbital effect and reveal that the finite-momentum superconductivity is stabilized in the high magnetic field region. Furthermore, we predict the realization of unconventional finite-momentum superconducting state, in which both finite-momentum and zero-momentum Cooper pairs are stabilized and coexist.

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Effects of cis lifetime on photo induced orientational order parameter modulation

Soft Matter Physics Group Eiki Kawanishi

Abstract We evaluate the effects of cis lifetime and liquid crystal structure on molecular manipulation. By shortening cis lifetime, higher resolution orientational order parameter modulation is achieved.

Molecular manipulation is a method of controlling the concentration distribution of target molecules in a nematic liquid crystal containing azobenzene and target molecules [1]. The concentration profile of target molecules is controlled by inducing spatial variation of the order parameter. The order parameter is spatially modulated by local irradiation with excitation light to induce trans-cis photoisomerization of the azo molecules in the nematic liquid crystal. Because cis form azobenzene has a kinked shape (different from its trans form with a rod-like shape), the cis isomer can locally disturb orientational order in nematic liquid crystal.

In previous research on molecular manipulation, the orientational order parameter decreases outside the illuminated area due to diffusion of the cis isomer, reducing the spatial resolution with which molecular manipulation can be achieved [1]. To achieve sharper modulation of the order parameter, the amount of cis isomer outside the excitation area must be reduced. In a recent study, high resolution order parameter modulation by immobilization of cis isomer is achieved by polymerization of azobenzene [2]. However, the amount of cis isomer outside the excitation area depends on not only the diffusion coefficient of the cis form azobenzene but also its lifetime. If the lifetime of the cis isomer were short, any cis isomer which diffuses away from the excitation area would swiftly transform to the rod-like trans isomer; the decrease in order parameter outside the excitation area would then be small. Therefore, in this study, we explored the effect of cis lifetime on the resolution of spatial modulation of order parameter in nematic liquid crystal.

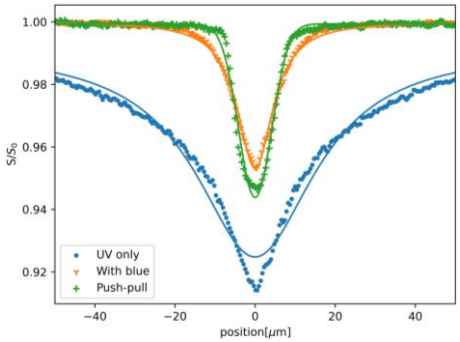

Fig.1 Orientational order parameter modulation. UV only (blue), simultaneous irradiation with blue light (orange), push-pull azobenzene (green)

Focusing on shortening the cis lifetime, we developed two methods to improve the resolution of order parameter modulation without any irreversible change of the sample by azobenzene polymerization. Firstly, we introduce simultaneous irradiation of the whole sample with blue light to photo-induce cis-trans back isomerization in addition to local UV light excitation. We also investigated using a different azo molecule, DR-1, which exhibits fast thermal back-isomerization (push-pull azobenzene). We compared two nematic liquid crystal samples, one containing 4,4’-diethoyxazobenzene, an azo derivative with long cis lifetime, and another containing DR-1, a push-pull azobenzene. 4,4’-diethoyxazobenzene shows trans-cis isomerization by UV light and cis-trans isomerization by blue light, while DR-1, which has short cis lifetime, is isomerized by blue light. Using the former sample, we applied local UV excitation only as a reference, and compared this with simultaneous blue light excitation over the whole sample in addition to local UV excitation. For the sample with DR-1, we simply applied local blue light excitation. Both methods, simultaneous blue light excitation and utilization of a push-pull azobenzene improved the resolution of spatial modulation of orientational order parameter compared with UV light only excitation (Fig.1). Using a push-pull azobenzene led to a faster spatial decay than simultaneous blue light irradiation.

Based on the above results, we conclude that a shorter cis lifetime reduces the amount of cis isomer outside the excitation area and improves the spatial resolution of order parameter modulation in a nematic liquid crystal.

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Quantum Cryptographic Primitives with Certified Everlasting Security

YITP, Quantum Information Taiga Hiroka

Abstract: We formalize and construct new inherently quantum cryptographic tasks called quantum cryptography with certified everlasting security. In the primitives, computational security is ensured by default. Furthermore, one can check if the encrypted data is deleted or not. Once the deletion is confirmed, the security becomes information theoretical security.

Quantum mechanics enables new cryptographic applications that are fundamentally impossible with classical cryptography. Discovering more cryptographic applications of quantum mechanics is crucial. In this work, we introduce a novel application called "quantum cryptography with certified everlasting security."

In cryptography, security is typically categorized to either information-theoretical or computational security. Ideally, we should achieve information-theoretical security because it ensures security against adversaries with unbounded computational resources. However, achieving information-theoretical security is shown as impossible for various cryptographic tasks even in the realm of quantum [1]. Consequently, many works explore cryptography with computational security. The drawback, though, is that computational security only ensures the security against current computing resources. Future unexpected advances, such as drastically new algorithms or powerful computing devices, may render these schemes insecure in the future.

In our work [2,3], for various cryptographic primitives, we formalize a new security called "certified everlasting security", which offers a compromise of information-theoretical security. In this security, computational security is ensured by default. Moreover, one can verify whether the adversary deletes the encrypted data. After receiving the data, the adversary can issue a deletion certificate proving that the data has been deleted. Once a valid certificate is issued, the scheme changes to information-theoretical security, and hence even unbounded adversaries cannot obtain the information of data. While certified everlasting security is weaker than information-theoretical security—since a malicious adversary might refuse to issue a valid certificate—it remains meaningful. For instance, penalties could prevent a malicious party from refusing to issue the certificate.

We construct several cryptographic primitives with certified everlasting security by applying quantum mechanics[2,3]. Certified everlasting security is impossible with classical cryptography. If the encrypted data is a classical bit string, the adversary can freely clone it and hence the scheme must be secure against unbounded adversaries from the point it receives the data. This argument cannot be applied to the quantum case, because the measurement may alter the quantum state. In our work, we construct certified everlasting versions of various cryptographic primitives by exploiting quantum properties in a clever way. Our construction includes public-key encryption, zero-knowledge proofs, functional encryption, and so on. These primitives are typically deemed impossible to achieve with information-theoretical security. Compared to prior constructions, our protocol remains secure against computationally unbounded adversaries once deletion is confirmed.

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Pressure Evolution of Magnetic Structures and Quasiparticle Excitations on Rare-Earth-Based Zigzag-Chain $YbCuS_2$

Quantum Materials Lab. Fumiya HORI

Abstract A rare-earth-based semiconductor $YbCuS_2$ exhibits unique magnetic properties due to the frustration from Yb zigzag chains. Our nuclear quadrupole resonance measurements revealed that pressure changes the magnetic structures and suppresses the gapless excitations, modifying the exchange interactions. Our findings are consistently understood with the anisotropic spin models proposed recently.

Frustrated magnets based on rare-earth elements with 4*f* electrons have garnered significant attention in recent years [1-3]. This is because anisotropic exchange interactions, arising from the strong spin-orbit coupling and crystal field effects of the 4*f* electrons, lead to the emergence of novel magnetic states not observed in simple spin-1/2 Heisenberg frustrated magnets [1]. For example, $YbMgGaO_4$ [2] and $NaYbSe_2$ [3] with the Yb^{3+} triangular lattices have been proposed to exhibit exotic ground states, such as Z_2 spin liquids and spinon Fermi surfaces.

$YbCuS_2$ is such a rare-earth-based frustrated semiconductor. In this compound, the Yb^{3+} ions form the zigzag chains, and the frustration effect is expected due to the competition between the nearest neighbor J_1 and next-nearest neighbor J_2 exchange interactions. In fact, we have revealed several unique properties arising from the frustration effect on $YbCuS_2$ so far [4, 5]. $YbCuS_2$ exhibits a first-order antiferromagnetic (AFM) transition at T_N ~ 0.95 K and an incommensurate AFM structure with a tiny ordered moment below T_N was suggested by our $^{63/65}$Cu-nuclear quadrupole resonance (NQR) measurement [4, 5]. In addition, the nuclear spin-lattice relaxation rate $1/T_1$ is proportional to T^1 below 0.5 K, which is generally observed in gapless phenomena. This *T*-linear behavior cannot be explained by conventional magnon excitations and indicates the emergence of the gapless charge-neutral quasiparticle excitations in $YbCuS_2$ [4, 5]. However, the origin and characteristics of the gapless excitations remain unclear. After our experimental study, it has been theoretically proposed that the anisotropic exchange interactions originating from the Yb zigzag chains may give rise to gapless emergent quasiparticles called “nematic particles”, which explain our NQR results [6, 7]. In addition, the proposed spin model predicted a ground-state phase diagram featuring a “quantum Lifshitz multicritical point”, where five different phases converge at one point [6, 7]. Therefore, experimental investigations on $YbCuS_2$ by changing the exchange interactions are promising for finding exotic phenomena.

Based on such motivation, we performed the NQR measurements under pressure [8]. Under pressure of 1.6 GPa, T_N increases to 1.17 K. As shown in the Fig. 1, the analysis of the NQR spectrum at 1.6 GPa revealed that the incommensurate magnetic structure at ambient pressure changes to a commensurate one, which can be regarded as an odd-parity magnetic multipole order with both space-inversion and time-reversal symmetries broken. Interestingly, pressure reduces the value of $1/T_1$ at low temperatures, indicating the suppression of the gapless quasiparticle excitations. These findings suggest that pressure changes the exchange interactions between Yb^{3+} ions, affecting both the magnetic ground state and the quasiparticle excitations. Our findings are consistently understood with the above-mentioned spin model with the rare-earth-based anisotropic exchange interactions [6, 7] and highlight the richness of the one-dimensional nature and the significance of the anisotropy in this system.

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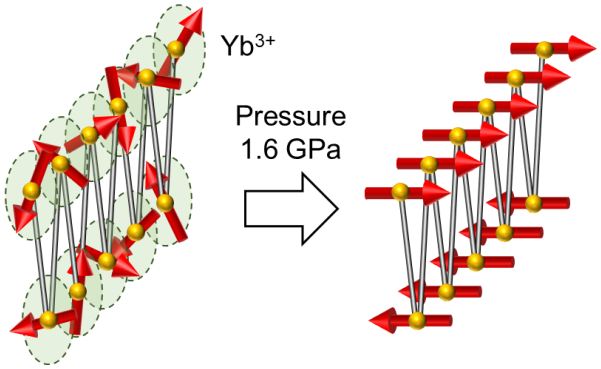

Fig. 1: Schematic image of magnetic structures in $YbCuS_2$.

Impact of Charge Distribution on the Stability of Ferroelectric Nematic Liquid Crystals

Statistical Physics Dynamics Group Matheus de Mello

Abstract Using atomistic simulations, we explore the physical mechanism behind the long-range polar order in the ferroelectric nematic liquid crystal DIO, with a focus on the influence of its charge distribution and molecular shape. Our findings highlight the critical role of the correlation between the lateral local dipoles in polar ordering.

The 100-year-old long search for a liquid-crystalline phase with global polar order made significant advances when Nishikawa et al. [1] and Mandle et al. [2] independently discovered the ferroelectric nematic phase, characterized by novel, lightweight rodlike molecules, DIO and RM734. This phase is distinguished by its high dielectric permittivity, nonlinear electro-optical properties, and fluidity, positioning it as a promising alternative for technological applications, surpassing traditional ferroelectric solids.

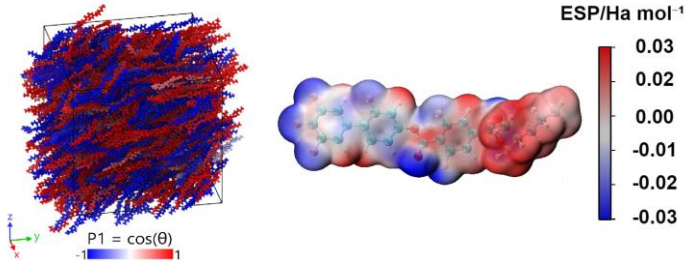

Fig. 1. Snapshot of atomistic simulation of a weakly ordered ferroelectric phase and the corresponding electrostatic isopotential surface map of DIO molecule.

Our objective is to understand the mechanism and stability underlying the phase transition to a long-range polar nematic state, focusing on whether the phase transition is driven by dipole-dipole electrostatic interactions [3] or by the molecules' tapered shape [4]. In this study a comprehensive atomistic simulation of charged and chargeless topologies of DIO molecules within the ferroelectric nematic phase was investigated.

In charged DIO topologies, the research demonstrates a favorable alignment of molecules in head-to-tail and parallel side-by-side arrangements, adopting a correlated orientation that promotes polar ordering. In contrast, chargeless DIO topologies exhibit no polar ordering, with molecules aligning antiparallel, although they still form an apolar nematic phase. This distinction suggests that molecular shape is not a key factor in ferroelectric ordering, at least in DIO. While Madhusudana suggested that an alternating charge distribution along the molecule's long axis could induce polar ordering [5], our results indicate that this effect alone is insufficient.

The spatial and orientational correlation functions, along with dynamic behaviors, were analyzed. We highlight the importance of charge asymmetry, through lateral local dipoles in the molecular structure, and short-range electrostatic interactions in stabilizing long-range polar order. We hope that our results advance the field of polar nematics with potential technological applications in low voltage displays, memory devices, sensors, and energy harvesting.

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Dynamic Heterogeneity in Mesoscale Turbulence of Dense Living Matter

Dissipative Structure and Biological Physics Laboratory　Kohei Okuyama

Abstract Active systems of self-propelled particles show diverse dynamic orders, especially at high densities, where understanding emergent phases is challenging. Using *Tetrahymena* as a model microswimmer, we experimentally observed their collective dynamics in dense conditions, revealing density-dependent dynamics and characteristics like active turbulence and dynamic heterogeneity.

Active matter systems, comprising objects that possess degrees of freedom for self-propelled motion, exhibit various forms of dynamic order across multiple scales. A central challenge in this field is the characterization and classification of the emergent dynamical phases in assemblies of self-propelled particles. A striking feature of collective motion is that local interparticle interactions ultimately give rise to globally coherent structures as highlighted in seminal work [1]. While our fundamental understanding of active systems in dilute regimes is nearly established, ongoing efforts are focused on exploring their universal properties in highly condensed regimes. Key phenomena include active turbulence [2], where coherent vortex structures continually form, and active glass [3], which, like classical glass or granular systems, shows a sharp increase in relaxation time as density rises. However, how these phenomena transition into one another on a phase diagram spanned by various particle properties and order parameters remains elusive.

We conducted experimental studies on collectives of the microorganism *Tetrahymena*, a ciliate used as a model system for dense active matter [4]. Using machine learning techniques, we successfully achieved long-term tracking of thousands of cells even in densely packed conditions. Our results show density-dependent growth in the correlation length scale of dynamics. We revealed that this dynamical order can be characterized by two key aspects: active turbulence and dynamic heterogeneity. Our findings provide a fresh perspective on dense active systems and offer insights into cellular tissues, which represent the condensed limit of particle-dispersed systems.

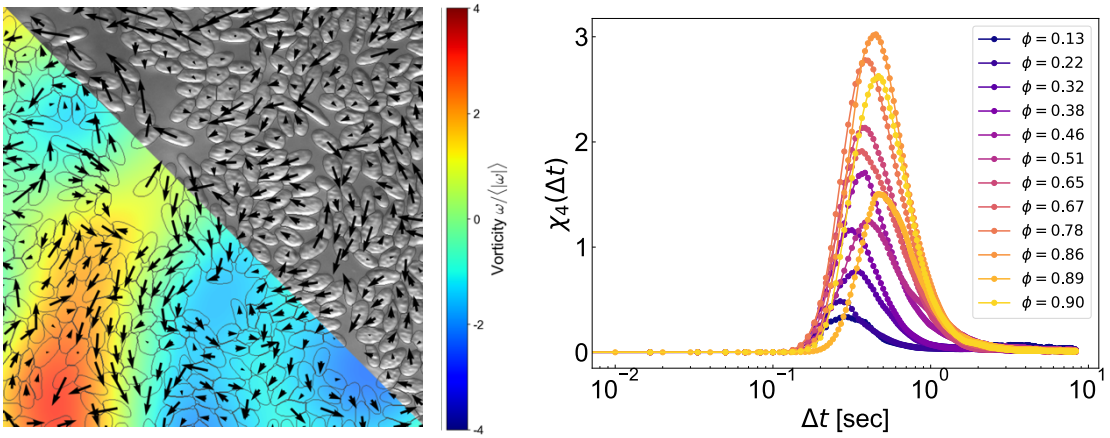

Fig. 1. (Left) Experimental image overlayed with cell velocity (upper right) and vorticity field (color, lower left). (Right) Density-dependent growth of dynamic susceptibility χ_4.

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Topological enhancement of non-normality in non-Hermitian skin effects

Yukawa Institute for Theoretical Physics, Yusuke Nakai

Abstract We introduce scalar measures that adequately characterize non-Hermitian skin effects under the open boundary condition. Using these measures, we reveal that the topological properties of the non-Hermitian skin effect give a macroscopic enhancement of non-normality under the open boundary condition. The topological enhancement of non-normality governs the perturbation sensitivity of the spectra and the anomalous time-evolution dynamics intrinsic to non-Hermiticity.

In recent years, there has been growing interest in non-Hermitian systems, where dynamics are governed by non-Hermitian operators [1]. In condensed matter physics, such operators emerge in various contexts. For example, in certain types of open quantum systems, particle and energy exchange with the environment can lead to time evolution governed by non-Hermitian operators.

Non-Hermitian operators exhibit mathematical properties that are absent in Hermitian operators. For instance, while the eigenvalues of Hermitian operators are always real, those of non-Hermitian operators can be complex. Additionally, the complex conjugate of a right eigenvector of a non-Hermitian operator is not necessarily equal to its corresponding left eigenvector.

These mathematical properties give rise to phenomena unique to non-Hermitian systems. One such phenomenon is the non-Hermitian skin effect, where the right eigenstates and their corresponding left eigenstates localize at opposite edges of the system, and the bulk spectrum strongly depends on the boundary conditions [2]. While non-Hermitian skin effects are characterized by non-trivial topology under the periodic boundary condition [3], there is no proper scalar measure to characterize non-Hermitian skin effects under the open boundary condition.

In this presentation, we introduce new scalar measures to properly characterize non-Hermitian skin effects under the open boundary condition. These measures quantify the non-normality of a matrix, capturing the two key properties of the skin effects. We show that the topological nature of non-Hermitian skin effects significantly enhances non-normality on a macroscopic scale under the open boundary condition. Additionally, through concrete models, we demonstrate that this enhanced non-normality accurately describes the topological phase transitions caused by the interplay between non-Hermitian skin effects and disorder (Fig. 1). Finally, we reveal novel, fundamental properties in non-Hermitian physics by focusing on the enhanced non-normality. Specifically, we show the topological enhancement of non-normality due to non-Hermitian skin effects leads to extraordinary sensitivity to perturbations and anomalous time evolution of dynamics [4].

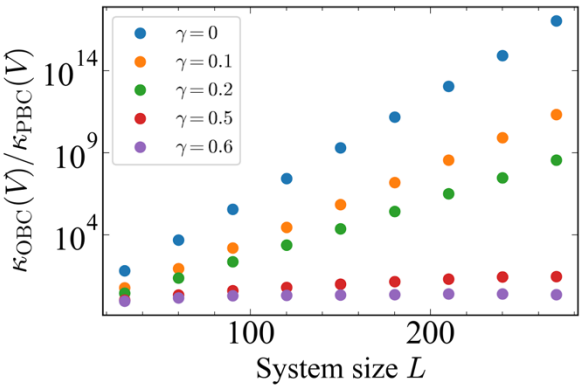

Fig.1: Topological enhancement of non-normality.

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