平 成 ２ ８ 年 度

京 都 大 学 大 学 院 理 学 研 究 科

Ｄ Ｃ ３ 回 生 研 究 発 表 会
要旨集

２０１６年１１月２２日（火）

物 理 学 第 一 分 野

物理学第一分野ＤＣ３回生研究発表会

場所：理学研究科５号館　５階・第四講義室
発表：１５分（別に質問１０分程度）

２０１６年１１月２２日（火）９：００～　開始

目　　次

1. Visualization of Chiral Domain Structure in Chiral Superfluid ^{3}He-A
笠井　　純（　９：００）

2. Modifying Structure and Adhesion in Thin films and Membranes
GIBBONS, Andrew（　９：２５）

3. Membrane fluctuation and shape deformation with continuous flow of water permeating lipid bilayer
鴻巣　正樹（　９：５０）

4. Geometrical responses in topological materials
住吉　浩明（１０：１５）

１０：４０～１０：５０　休憩

---

5. Nonlocal interaction of light with weakly confined excitons
高畑　光善（１０：５０）

6. Laser-induced Kondo effect and topological phases in ultracold alkaline-earth atoms
中川　大也（１１：１５）

7. Gap classification of multi-orbital Superconductors and non-symmorphic Superconductors
野本　拓也（１１：４０）

8. Topological Aspects of Cold Atoms in Optical Superlattice
松田　冬樹（１２：０５）

１２：３０～１３：３０　昼休み

---

9. Study of superconducting gap structure in prototypical heavy-fermion $CeCu_2Si_2$
山下　卓也（１３：３０）

10. Mechanism of excitonic valley coherence in monolayer transition metal dichalcogenides

吉川　尚孝（１３：５５）

11. Quasiparticle excitations in FeSe in the vicinity of BCS-BEC crossover studied by thermal transport measurements

綿重　達哉（１４：２０）

12. Geometric Fluctuation Theorem

渡邉　航太（１４：４５）

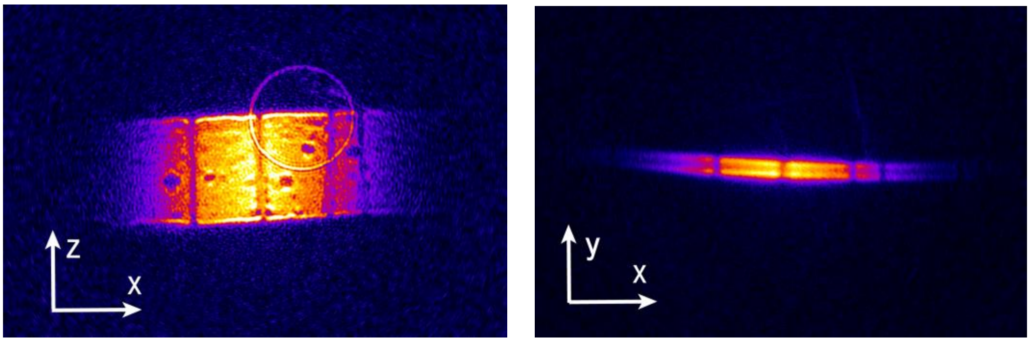
Visualization of Chiral Domain Structure in Chiral Superfluid ^{3}He-A

Low Temperature Physics Laboratory   Jun Kasai

Abstract We established a spectroscopic NMR imaging technique. By using this technique, we visualized planar defects in superfluid ^{3}He-A and identified them as chiral domain walls. Those structures were stable for a long time in sufficiently low temperature.

Superfluid ^{3}He-A is well known as a chiral superfluid whose Cooper-pairs orient the orbital angular momentum toward the same direction. In general, two ground states which have chiralities of +1 and -1 are degenerated. Around a chiral domain wall which exists between two domains of opposite chiralities, the existence of edge mass current owing to intrinsic orbital angular momentum is predicted but it has not been studied experimentally at all. Ikegami *et al.* reported an indication that chiral multi-domain are formed on a free surface of ^{3}He-A [1]. However there have ever been no way to observe where chiral domain walls are.

We established an advanced NMR imaging technique, Magnetic Resonance Spectroscopic Imaging (MRSI), which makes it possible to extract the local NMR spectra with a spatial resolution of a few ten micrometers. With NMR imaging we discovered planar defects of ^{3}He-A in a slab geometry, shown in Figs.1. Topological defects which appear in superfluid ^{3}He can be identified by NMR frequencies. Detailed analysis of local NMR spectra tells that the planar defects had almost the same frequency as the ground state, and locally broadened NMR line width. Comparison with numerical simulation identified these planar defects as the dipole-locked soliton. It is topologically unstable in bulk volume, but in our experimental situation it is stabilized by chiral domain walls pinned at the surface of the container. Therefore we succeeded in visualization of the chiral domain structure in chiral superfluid for the first time. Those structures were naturally formed by cooling into the superfluid phase and different patterns appeared in each cooling. They were metastable but unchanged below T/Tc = 0.9 for a long time (> 1 day).



(a) (b)

Fig. 1 MRI images of planar defects in ^{3}He-A. (a) is the front view and (b) is the top view of the slab. Several dark lines lying across the bright bar shapes which represent the spatial distribution of ^{3}He, are chiral domain walls.

References

[1] H. Ikegami, Y. Tsutsumi and K. Kono, J. Phys. Soc. Jpn., **84**, 044602 (2015)

Modifying Structure and Adhesion in Thin films and Membranes

Solid State Spectroscopy Group Andrew Gibbons

Abstract Using phase separation of block copolymers, porous thin films membranes have been developed for ultrafiltration. Additives have been used to tune the structure and adhesion properties of the membranes.

Thin film polymer membranes are an attractive solution to the problem of making filter membranes with tunable and flexible properties. Phase separation of block copolymers can be used to produce films with long range porous structure [1]. A problem with many types of polymer membrane is the build-up and adhesion of organic materials. This material is not easily removed and reduces the efficiency and longevity of filter membranes [2]. The topic of this presentation is the modification of block copolymer membranes for membrane filtration applications.

Block copolymer membranes were developed with surfactant additives to reduce adhesion on the membrane surface. The block copolymer membranes of polystyrene-*block*-poly(methyl methacrylate) [PS-*b*-PMMA] were developed using a self-assembly phase inversion technique to create porosity within the membrane. A well characterized triblock copolymer of the Pluronic™ commercial series, made of blocks of polyethelene oxide and polypropylene oxide, was used as an additive in the PS-*b*-PMMA film. Pluronic is a surfactant and its addition increases the hydrophilicity of the surface resulting in a reduction of the adhesion of proteins on the surface [3].

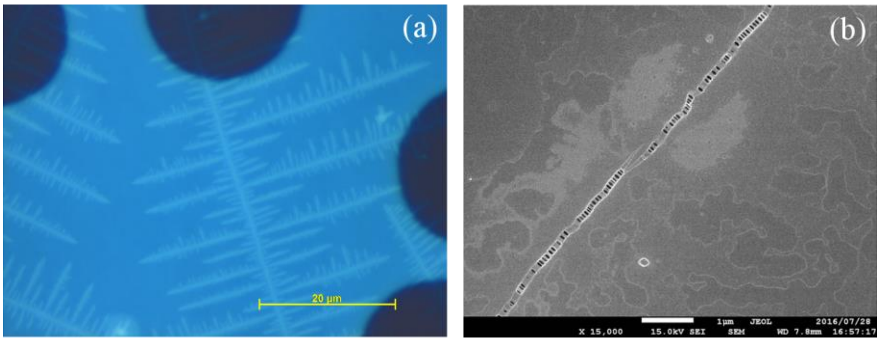


Fig.1 Variation of Pluronic concentration in PS-b-PMMA film can results in different film structures. The optical microscope image (a) shows 10 wt % Pluronic producing crystalline growth of Pluronic at crack interfaces. SEM image (b) shows beginning of crack development at the nanoscale with 5 wt % Pluronic.

The effect of the Pluronic on the properties of the PS-b-PMMA membranes was examined in detail. Addition of Pluronic results in an increase of the films hydrophilicity, as measured by contact angle. Above certain concentrations the Pluronic also results in the formation of monolayers of dendritically crystallized Pluronic surface layers, macrophase separation of the two mixed block copolymers and then much larger crack structures within in the film, as shown in Fig.1 . The triple level of complexity in the resulting structure offers interesting possibilities for altering nucleation and growth of adhesive layers during adsorption processes; therefore the resulting materials, through careful tuning of their structures via a range of parameters, offers an interesting system for observing adhesion over multiple length scales.

References

[1] H. Ahn, *et al.*, ACS Nano, **8**, 11745-11752 (2014).
[2] T. Nguyen *et al.*, Membranes, **2**, 804-840, (2012).
[3] Y.Q. Wang, *et al.*, Journal of Membrane Science, **283**, 440-447 (2006).

Membrane fluctuation and shape deformation with continuous flow of water permeating lipid bilayer

Dissipative structure and Biological physics laboratory Masaki Konosu

Abstract We investigate the influence of the continuous flow of water permeating lipid membrane on shape deformation and fluctuation of giant vesicles. As a result, we find new tubular morphology of lipid membrane. Furthermore, we discuss the kinetic model of a membrane in the context of soft matter physics on a lipid membrane and hydrodynamics on the solvent.

Lipid bilayer membranes can exhibit a rich variety of shape transformation due to their mechanical flexibility, which is adapted to a living system to express many cellular functions. Notably, shape deformation of lipid membrane is known to be crucial in dynamic processes such as endocytosis, exocytosis, forming cell organelles and cell death [1]. Giant unilamellar vesicles (GUVs) are suitable to observe their live deformations by optical microscopy. Lipowsky and his co-workers have studied highly curved membrane structures such as budding and tubular structures of GUVs experimentally and theoretically, where such structures were known as the case driven by the spontaneous curvature and thermal fluctuation of a membrane [2].

We studied the influence of the continuous osmotic flow of water permeating lipid membrane on shape deformation and membrane undulation although the change in osmotic pressure results in the decrease in the internal volume of the semi-permeable membrane of GUVs. The system that the concentration of sorbitol solution in bulk linearly increases was developed using a perfusion chamber with syringe pumps and allowed to observe shape deformation of each GUV with the continuous flow of water. Eventually, we made phase diagram of shape deformation for the magnitude of permeation flow and found the tubular structure after a drastic fluctuation when the water diffusion from the inner to the outer of a membrane was significant (Fig.1).

The goal of this study is to understand the role of mechanics in a growth of such highly curved membrane structures. Physical properties gathered for GUVs with and without the permeation flow were power spectrum and relaxation time of a flaccid membrane before the protrusion, both of which depend on the spatial frequency of fluctuation. As a result, the dependencies on wave number in the case of insignificant efflux of water were the same as the previous studies based on elastic energy minimum and thermal noise [3]. In the case of massive efflux of water, however, the dependencies deviated from ones without the permeation flow. We discuss why the physical properties change and the equation of motion on unstable lipid bilayer.

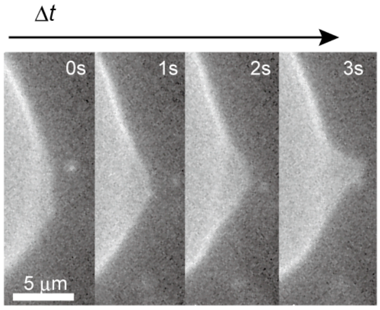


Fig. 1. Osmotic permeation flow-induced protrusion of lipid bilayer after perfusion of a hypertonic solution of sorbitol.

References

[1] B. Alberts, *et al.*, “Molecular Biology of the Cell” (Garland Science, New York, 2002).

[2] H.-G. Döbereiner, *et al.*, Eur. Biophys. J. 28, 174 (1999).; R. Lipowsky, Biol. Chem. 395, 253 (2014).

[3] J. Pécréaux, *et al.*, Eur. Phys. J. E 13, 277 (2004).; R. Rodríguez-García, *et al.*, Phys. Rev. Lett. 102, 128101 (2009).

Geometrical responses in topological materials

Condensed matter theory group　Hiroaki Sumiyoshi

Abstract Using a technique of the theory of gravitation, we derive the Berry-phase formula for the thermal Hall effect in chiral superconductors and demonstrate that a new topological response referred to as the torsional chiral magnetic effect occurs in Weyl semimetals owing to a fictitious magnetic field due to lattice defects.

Recent both theoretical and experimental studies have revealed that topological materials such as topological insulators and superconductors, graphene, and Weyl semimetals exhibit characteristic transport properties associated with the geometrical structures of the wave functions of the electrons in the real and momentum spaces. In addition to applying electromagnetic fields, these responses are also caused by external forces, such as applying a temperature gradient, twisting the sample, making dislocations in the lattice. Theoretically, they are described by the technique of the differential geometry. Based on these backgrounds, in this work, we theoretically, studied two geometrical transport phenomena in topological materials, using this technique.

First, we study on the thermal Hall effect in superconductors with broken time-reversal-symmetry [1]. The thermal Hall effect is the thermal analog of the Hall effect and the production of a temperature gradient by the transverse temperature gradient, and is important for detecting the topological feature of the superconductors rather than the Hall effect, since the number of electrons is not conserved and then electromagnetic responses hardly grasp it. We derive a formula for the thermal Hall coefficients, represented by the Berry-curvature of the Bogoliubov-de Gennes (BdG) Hamiltonian. We also applied it to two-dimensional chiral superconductors, and found that in the low temperature limit, the thermal Hall coefficient are quantized as, $\kappa = c\pi T/6$, where c is one-half of the bulk Chern number defined from the BdG Hamiltonian and corresponds to the central charge of the Majorana edge mode. It reproduces the result of a previous study from edge calculations [2], but can be applied for any superconductors even with nodes including Weyl superconductors, and therefore useful for discovering broad types of topological materials.

Second, we propose a new topological response, referred to as the torsional chiral magnetic effect (TCME), in Weyl semimetals. Weyl semimetals are materials, which are characterized by one or more pairs of Weyl cones protected by topological numbers, and many exotic transport phenomena have been theoretically predicted and some of them are observed in the materials [3]. The TCME is the generation of a ground state current along an edge or screw dislocation line (Fig.1). We investigate it by using the quantum field theory with background geometry. We also confirm the effect from a numerical calculation of realistic lattice models of Weyl semimetals.

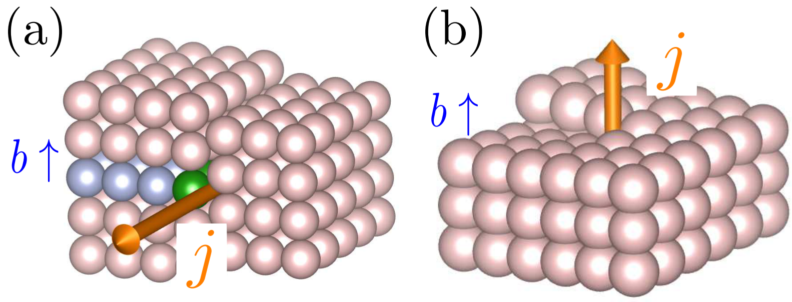


Fig. 1. Torsional chiral magnetic effect due to (a) edge and (b) screw dislocations. Reproduced from [4].

References

[1] Hiroaki Sumiyoshi and Satoshi Fujimoto, J. Phys. Soc. Jpn. **82**, 023602 (2013).

[2] N. Read and D. Green: Phys. Rev. B **61,** 10267 (2000).

[3] For review: P. Hosur and X. Qi, Comptes Rendus Physique **14**, 857 (2013).

[4] Hiroaki Sumiyoshi and Satoshi Fujimoto, Phys. Rev. Lett. **116**, 166601 (2016).

Nonlocal interaction of light with weakly confined excitons

Solid-State Spectroscopy Group Mitsuyoshi Takahata

Abstract We have observed film thickness dependences of the radiative recombination rate of excitons in Cu_2O by micro-photoluminescence measurements. This is the first demonstration of size-resonance enhancement of the coupling between weakly confined excitons and light by nonlocal response of an excited state.

Interaction between light and matter has been studied in many fields, such as physics, chemistry, and information technology. Recent advances in sample fabrication techniques opened up opportunities to explore excited states with a coherence length extending over the wavelength of light, and light modes enhanced with metal nanostructure in a molecular scale. In such a situation, the interaction of light and matter is expected to be enhanced due to nonlocal optical response [1] beyond the long wavelength approximation. We demonstrated size-resonance enhancement of radiative coupling with weakly confined excitons using a high-quality Cu_2O thin film, where Cu_2O is known for the long exciton lifetime [2] and giant Rydberg exciton states [3].

Figure 1(a) shows photoluminescence (PL) spectra of the 2p-4p yellow excitons under continuous-wave laser excitation of a Cu_2O thin film at 2.33 eV. The PL spectral width (FWHM) and the PL intensity of 2p excitons periodically varied depending on the film thickness. As shown in Fig. 1(b), the peaks of the FWHM (squares) appeared at thicknesses different from those for the intensity (circles). The FWHM of 2p excitons in bulk Cu_2O is known to be caused by non-radiative relaxation involving phonon emission [4]. Since the non-radiative relaxation rate is unchanged with respect to the film thickness, the varying FWHM observed in the film is attributed to the change in the radiative width. The solid lines were calculated using the Green's function approach to the nonlocal response [1]. The good agreement between the experimental results and calculations clearly demonstrates that the radiative recombination rate of 2p excitons is enhanced due to the nonlocal response depending on the film thickness.

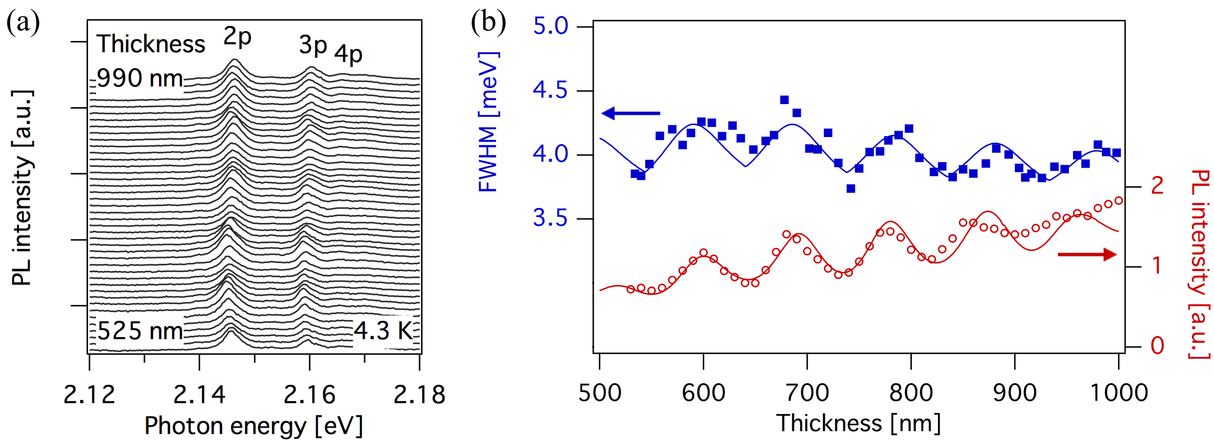


Fig. 1: (a) PL spectra of a Cu_2O thin film at 4.3 K, measured in steps of about 10 nm thickness. (b) Thickness dependence of FWHM (squares) and intensity (circles) of 2p exciton PL in comparison with calculations assuming nonlocal response (solid lines).

References

[1] L. Q. Phuong, M. Ichimiya, H. Ishihara, and M. Ashida, Phys. Rev. B, **86**, 235449 (2012).
[2] S. Koirala, M. Takahata, Y. Hazama, N. Naka, and K. Tanaka, J. Lumin. **155**, 65 (2014).
[3] T. Kazimierczuk, D. Fröhlich, S. Scheel, H. Stolz, and M. Bayer, Nature, **514**, 343 (2014).
[4] T. Kitamura, M. Takahata, and N. Naka, submitted to Phys. Rev. B.

Laser-induced Kondo effect and topological phases in ultracold alkaline-earth atoms

Condensed matter theory group Masaya Nakagawa

Abstract We propose that intense laser fields can induce a novel Kondo effect in ultracold alkaline-earth atoms. The Kondo effect overcomes the heating effect caused by the irradiation and shows several peculiar properties which originate from the laser-spin coupling. We also demonstrate that this system hosts a symmetry-protected topological phase in one dimension.

Kondo effect appears ubiquitously in condensed matter systems. This effect arises from the screening of a localized magnetic moment by a surrounding fermion cloud, and leads to the formation of a many-body entangled state called Kondo singlet between them, as a consequence of interplay of Fermi statistics and strong interactions. The Kondo effect is thus an important phenomenon for condensed matter physics not only as a typical example of quantum many-body effects, but also as a source of many-body quantum entanglement. For example, the Kondo effect is one of the keys to understand correlation effects in various rare-earth materials, where the Kondo singlet at every lattice site ("Kondo lattice") leads to the formation of heavy fermion liquids with highly renormalized quasiparticles. The Kondo lattice is also a significant platform to realize topological phases with strong interactions, known as topological Kondo insulators, where the quantum entanglement is indispensable.

In this study, we propose that intense laser application to atoms can coherently induce a novel Kondo effect in ultracold atomic gases [1]. In this setup, two long-lived metastable electronic states of alkaline-earth atoms play the role of localized moments and a fermion cloud respectively, and the Kondo effect is induced by optical transitions between these two internal states. One of the problems addressed here is whether the quantum many-body effect (the Kondo effect) survives or not in nonequilibrium situations under strong irradiation. We demonstrate that the optically coupled two internal states are dynamically entangled to form the Kondo singlet state, and they actually overcome the heating effect caused by the irradiation. Furthermore, it is shown that the laser-induced Kondo effect has several peculiar properties, which cannot be realized in ordinary solid-state systems. For example, a lack of SU(N) symmetry in the optical coupling gives spin-selective heavy fermion liquids in which higher spin components have larger effective masses. We further found that the laser-induced Kondo effect has unusual spin states different from the well-known Kondo singlet. This unusual Kondo state is certainly distinct from the ordinary Kondo singlet state, if we assume the spin π-rotational symmetry along the x axis.

In addition to such properties, the cold-atom realization of the Kondo lattice can host a topological phase protected by symmetries, in one spatial dimension with tightly confined optical lattices. This phase is reminiscent of the celebrated Haldane phase in spin chains, but here the charge degrees of freedom play a key role on the fate of the topological phase. We uncover the role of various symmetries on the phase diagram of the one-dimensional Kondo lattice, using field-theoretical methods and characterization with matrix product states. The one-dimensional Kondo lattice provides a typical example of a crossover from fermionic topological phases in weakly interacting regime to bosonic topological phases in the strong coupling limit, and ultracold alkaline-earth atoms are a promising candidate to realize the symmetry-protected topological phase.

References

[1] M. Nakagawa and N. Kawakami, Phys. Rev. Lett. **115**, 165303 (2015).

Gap classification of multi-orbital Superconductors and non-symmorphic Superconductors

Condensed Matter Theory group Takuya Nomoto

Abstract Motivated by a growing interest in multi-orbital superconductors with spin-orbit coupling, we perform the group-theoretical classification of gap structure in symmorphic/non-symmorphic space groups. Our study shed light on several possibilities; the E_{2u} pairing state in UPt_3, electron-phonon mediated anisotropic pairing states, and hidden symmetry-protected nodes in UCoGe and UPd_2Al_3.

Classification of superconducting gap functions in single-orbital systems (See a review by M. Sigrist and K. Ueda [1]) is indispensable for an analysis of nodal structure in various unconventional superconductors. However, attention should be paid in its use, since the actual gap structure does not exactly have such a simple momentum dependence summarized in tables of Ref. [1]. A remarkable example is an exotic multi-gap structure in a heavy-fermion superconductor UPt_3, which we found from a gap analysis based on the first-principles calculations [2]. The obtained E_{2u} state has in-plane twofold vertical line nodes, point and horizontal nodes on each Fermi surface, which is completely different from previous phenomenological models. It is very difficult to understand the nodal structure based on the classification of Ref. [1], and we need an explicit consideration of the *multi-orbital* character [2]. In addition, T. Micklitz and M. R. Norman demonstrated in their pioneering work that new types of symmetry-protected nodes can appear at the Brillouin zone boundary in *non-symmorphic* systems [3]. These facts imply importance of revisiting the classification of gap structure in symmorphic/non-symmorphic space groups by explicitly considering the multi-orbital character.

In the present study, we provide the group-theoretical classification of gap functions in the multi-orbital superconductors with spin-orbit interactions [4] and in non-symmorphic magnetic space groups [5]. In the former study, we perform the gap classification by introducing generalized Cooper pairs, which possess spin-orbital coupled (multipole) degrees of freedom, instead of the conventional spin singlet/triplet in the single-orbital systems. From the classification, we obtain the following consequences: (a) A gap function with $\Gamma^9 \otimes \Gamma^9$ in D_6 possesses nontrivial momentum dependence, which is different from the usual spin 1/2 classification. (b) Unconventional gap structure can be realized in the BCS approximation for a purely local interaction. This fact implies emergence of the electron-phonon mediated unconventional superconductivity.

Furthermore, we extend the gap classification to the non-symmorphic magnetic space groups, which have been less understood in spite of the growing interest in superconductors coexisting with magnetism. The results are applied to the analysis of superconductivity in UCoGe and UPd_2Al_3. Based on the weak-coupling BCS theory, we show that the UCoGe-type ferromagnetic superconductors must have horizontal line nodes on either k_z=0 or $k_z=\pm\pi/c$ plane. On the other hand, in UPd_2Al_3-type antiferromagnetic superconductors, A_g symmetry possesses line nodes in antiferromagnetic Brillouin zone boundary perpendicular to *c*-axis, namely, the conventional fully-gapped *s*-wave superconductivity is forbidden irrelevant to the pairing mechanism. Therefore, UCoGe and UPd_2Al_3 are candidates of unconventional superconductors possessing hidden symmetry-protected line nodes, peculiar to non-symmorphic magnetic space groups.

References

[1] M. Sigrist and K. Ueda, Rev. Mod. Phys. **63**, 239 (1991).
[2] T. Nomoto and H. Ikeda, arXiv:1607.02708 (to be published in Phys. Rev. Lett.).
[3] T. Micklitz and M. R. Norman, Phys. Rev. B **80**, 100506(R) (2009).
[4] T. Nomoto, K. Hattori, and H. Ikeda, arXiv:1607.02716 (to be published in Phys. Rev. B).
[5] T. Nomoto and H. Ikeda, arXiv:1610.04679.

Topological Aspects of Cold Atoms in Optical Superlattice

Condensed matter theory group   Fuyuki Matsuda

Abstract We study the topological aspects of cold atoms loaded on an optical lattice with an added optical superlattice potential. We find that the topological insulator-like behavior in this model can be understood clearly when we apply a mapping into higher dimensions, and that a set of weak Chern number determines the adiabatic pumping in the original 2D system. We also study the correlation effects in a 1D quasiperiodic superlattice.

Recently, experiments of cold atoms in an optical lattice are developing rapidly. It is possible to realize many different kinds of models on lattices and to control the interaction between particles with high flexibility by using cold atom systems. This technology is important not only for simulating theoretically well-known models, but also makes it possible to handle exotic models, which have not been realized in metals and alloys, such as new types of topological insulators [1], quasiperiodic systems [2], and so on.

On the other hand, mapping the hamiltonian between different dimensions plays an important role in understanding their physical properties. One of the significant examples of these mappings can be seen in the problem of the Hofstadter butterfly. Hofstadter mapped a two-dimensional (2D) system of square lattice under uniform magnetic field into a 1D equation, which is called the Harper equation [3]. Interestingly, a recent research of adiabatic pumping used this mapping in reverse, and showed the topological equivalence over a certain group of hamiltonians [4]. This kind of mapping into higher dimensions can be applied not only to 1D systems, but also to two and higher dimensional systems.

Motivated by these backgrounds, we consider a 2D tight-binding model of particles that hop on a square lattice in the presence of modulation in the on-site potential and the hopping amplitude, where the modulation amplitude only depends on the distance from an inclined line. We find that this model has a topological nature. First, we show that edge-localized states appear when the strong confining potential which constrain the particle around inclined line exists. Also, when we pay attention to energy spectra, these edge states cross the bulk energy band gap. These topological insulator-like behavior can be understood clearly when we map this 2D system into a 3D system. In the 3D mapped hamiltonian, a set of weak Chern numbers of this system becomes non-zero when the chemical potential is controlled adequately, which implies that this system is a weak topological insulator. This set of weak Chern numbers determine the adiabatic pumping in the original 2D system.

Furthermore, we study correlation effects in the 1D quasiperiodic model. We consider the 1D quasiperiodic Anderson-lattice model, which has quasiperiodically ordered impurities. The sites with an f-orbital are ordered as a “Fibonacci word”, one way to form 1D quasiperiodic orderings. To treat the correlation effect precisely, we use the density matrix renormalization group (DMRG) method. We show that the spin correlation function in the quasiperiodic system gives a characteristic pattern. Also, by analyzing the f-electron number and its fluctuation, we find that a valence transition, which usually occurs in the periodic Anderson model when the on-site interorbital interaction is large, is not sharp in the quasiperiodic system. Finally, we discuss the properties of the quasiperiodic Anderson-lattice model, comparing them against the Anderson-lattice model with randomly located f-orbitals. We find that the quasiperiodic Anderson-lattice model has a similar property to the periodic Anderson model for spin correlation, but also has a similar property to the Anderson-lattice model with randomly located f-orbitals for the valence fluctuation.

References

[1] G. Jotzu *et al.*, Nature **515**, 237 (2014).
[2] L. Fallani *et al.*, Phys. Rev. Lett. **98**, 130404 (2007).
[3] D. R. Hofstadter, Phys. Rev. B **14**, 2239 (1976).
[4] Y. E. Kraus *et al.*, Phys. Rev. Lett. **109**, 106402 (2012).

Study of superconducting gap structure in prototypical heavy-fermion $CeCu_2Si_2$

Quantum Condensed Matter Group Takuya Yamashita

Abstract We studied the superconducting gap structure and impurity effect on prototypical heavy-fermion $CeCu_2Si_2$. In contrast to long standing belief, we found full gap superconductivity with no sign change in this material. This leads to the surprising conclusion that strongly correlated electrons in heavy-fermion can condense into a fully-gapped *s*-wave superconducting state.

Strongly correlated electrons have been one of the most fascinating systems in modern physics. They exhibit a rich variety of exotic phenomena such as unconventional superconductivity, non-Fermi liquid, exotic orders and so on. The strongest electron correlation is realized in heavy-fermion (HF) compound, in which the quasiparticle effective mass is typically two or three orders of magnitude larger than the bare electron mass. In particular, such heavy quasiparticles often exhibit unconventional superconductivity in the vicinity of the magnetic instability, so-called quantum critical point (QCP).

$CeCu_2Si_2$ is a prototypical HF superconductor with T_c of 0.6 K discovered in 1979 [1]. The large specific heat jump at T_c indicates that the heavy electrons form Cooper pairs. The decrease of the Knight shift below T_c indicates the spin-singlet superconductivity [2]. Moreover, $T^{3/2}$ behavior in the resistivity and $T^{1/2}$ behavior in γ indicate that the superconductivity occurs in the vicinity of an antiferromagnetic (AF) QCP [3]. Unconventional nature of the superconductivity has been reported in some experiments, including the T-linear behavior of C/T [4], and no coherence peak just below T_c and the T^3 behavior in NMR relaxation rate $1/T_1$ [5]. Based on these results, the superconducting symmetry in $CeCu_2Si_2$ has been suggested to be *d*-wave with line nodes mediated by AF spin-fluctuations. On the other hand, recent specific heat measurements [6] suggested fully-gapped superconductivity. However, since the specific heat mainly detects the quasiparticle contribution in the heavy electron band, the possibilities of the existence of nodes in the light hole band cannot be excluded.

Here, to clarify the superconducting gap structure of $CeCu_2Si_2$, we performed the thermal conductivity (κ) measurements which sensitively probe the quasiparticle contribution in the light band. At the lowest temperatures in zero-field, κ/T extrapolated to $T = 0$ goes to zero within our experimental resolution or is at least an order of magnitude smaller than that expected for line nodes. Moreover, field dependence of κ/T shows that the magnetic field hardly affects the thermal conduction in the low field regime, which is in stark contrast to the nodal superconductor. Based on these results, we conclude the absence of gap nodes at any point on the Fermi surface. Furthermore, in order to clarify whether there is sign change in the superconducting gap, we performed the electron-irradiation experiments. We found a very small pair-breaking effect, which suggests there are no sign changes in the superconducting gap function.

These results imply that, contrary to long-standing belief, heavy electrons with extremely strong Coulomb repulsions can condense into a fully-gapped *s*-wave superconducting state, which has an on-site attractive pairing interaction [7].

References

[1] F. Steglich *et al.*, Phys. Rev. Lett. **43**, 1892 (1979).
[2] K. Ueda *et al.*, J. Phys. Soc. Jpn. **56**, 867 (1987).
[3] P. Gegenwart *et al.*, Phys. Rev. Lett. **81**, 1501-4 (1998).
[4] C. D. Bredl *et al.*, J. Magn. Magn. Mater. **31**–**34**, 373 (1983).
[5] K. Ishida *et al.*, Phys. Rev. Lett. **82**, 5353 (1999).
[6] S. Kittaka *et al.*, Phys. Rev. Lett. **112**, 067002 (2014).
[7] T. Yamashita *et al.*, submitted for publication.

Mechanism of excitonic valley coherence in monolayer transition metal dichalcogenides

Solid State Spectroscopy Group　　Naotaka Yoshikawa

Abstract We investigated the polarization dependence of the exciton photoluminescence and Raman scattering of CVD-grown monolayer MoS_2. We found that the photoluminescence become polarized accompanied by a drastic change of the polarization selection rule of Raman scattering under resonant excitation. We concluded that a domination of Raman component in the resonant second order optical process should be the mechanism of valley coherence.

The investigation of internal quantum degree of freedom is one of the most active research fields of condensed matter physics. The representative example is electron spin which connects with magnetic information storage, leading to the vast field of spintronics. The recent emergence of monolayer transition metal dichalcogenides such as MoS_2 and WSe_2 monolayers provides a new platform for exploring valley pseudospin and their potential for new electronics. These two-dimensional materials have a direct bandgap at the corners of the hexagonal Brillouin zone, that is, K and K' points. Because of the inversion symmetry breaking and strong spin-orbit interaction, the energetically degenerated exitons in K and K' valleys have the opposite spins and can be selectively excited using circularly polarized light. Robust valley polarization was demonstrated by the conservation of helicity in the exciton photoluminescence [1]. In addition, linearly polarized photoluminescence whose orientation coincides with that of the linearly polarized excitation from excitons was also observed in monolayer WSe_2 [2]. This indicates that excitons in different valleys may maintain their phase coherence in the recombination process because excitation with a linearly polarized photon generates a coherent superposition of the exciton states in K and K' valleys. The optical generation and readout of valley coherence are attracting much attention for quantum information applications using a valley pseudospin. However, the physical mechanism of valley coherence remains unclear, in particular, it has not been revealed how excitonic valley coherence can be kept under relaxation.

In this study, we investigated the polarization dependence of the exciton photoluminescence and Raman scattering of CVD-grown monolayer MoS_2, with circular and linear polarization and at a resonant and non-resonant excitation condition. Figure 1(a) shows linear polarization-resolved photoluminescence spectra at 34 K with resonant excitation. The exciton photoluminescence is strongly polarized, indicating the effective generation of valley coherence. In addition, spectrally narrow Raman peaks by phonons are also linearly polarized. The detection polarization dependence of the resonant Raman scattering is same as that of exciton photoluminescence as shown in Fig. 1(b). This indicates that the exciton photoluminescence is polarized just as the resonant Raman scattering is. Since the photoluminescence and Raman scattering cannot be distinguished under resonant excitation, they should be considered as a resonant second-order optical proces [3]. The resonant second order process should be a key to understanding the mechanism of valley coherence. By comparing the polarization dependence of photoluminescence and Raman scattering under non-resonant excitation with that under resonant excitation, it is indicated that the resonant second order optical process should be a key to understanding the mechanism of valley coherence. Considering the temperature dependence and theory of polarization selection rules, we concluded that the mechanism of valley coherence should be a domination of Raman component in the resonant second order optical process.

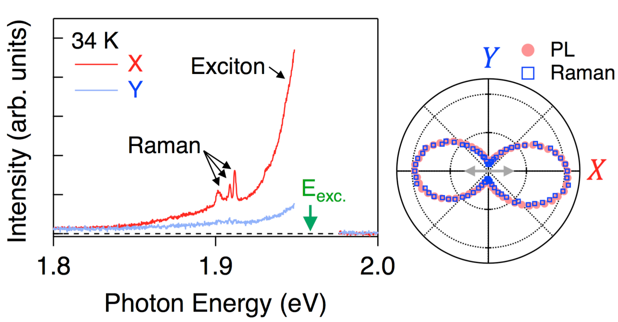


Fig. 1 (a) Linear polarization-resolved photoluminescence spectra with 1.96 eV excitation at 34 K. (b) Normalized intensity of photoluminescence and Raman scattering as a function of detection polarization angle.

References

[1] K. Mak *et al.*, Nature Nanotech. **7**, 494 (2012).
[2] A. Jones *et al.*, Nature Nanotech. **8**, 634 (2013).
[3] Y. Toyozawa *et al.*, J. Phys. Soc. Jpn. **42**, 1495 (1977).

Quasiparticle excitations in FeSe in the vicinity of BCS-BEC crossover studied by thermal transport measurements

Quantum Condensed Matter Group Tatsuya Watashige

Abstract To investigate the field-induced superconducting state (B-phase) in FeSe in the vicinity of BCS-BEC crossover, we performed the thermal Hall conductivity κ_{xy} measurements. Our results suggest that the B-phase is likely to a highly anomalous inhomogeneous superconducting state, rather than a conventional Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) state.

The iron-based superconductor FeSe has recently attracted growing interest because it exhibits several fascinating properties. The Fermi surface of FeSe consists of one small hole pocket at the Γ point and one or two small electron pockets at the M point. Remarkably, the Fermi energies of hole and electron pockets are extremely small, E_F^h ~ 15 meV and E_F^e ~ 10 meV, respectively [1,2]. FeSe is a multi-gap superconductor with two distinct superconducting gaps of $\Delta \approx 2.5$ and 3.5 meV [1,3] which are comparable to E_F. This strongly indicates that FeSe is located in the BCS-BEC crossover regime.

Recently, it has been reported a possible new field-induced superconducting phase (B-phase) in the low-temperature and high-field region (Fig. 1) [1]. In the B-phase, the Zeeman effect gives rise to highly spin-imbalanced superconducting state with the magnitude of the spin imbalance $P = (N_\uparrow - N_\downarrow) / (N_\uparrow + N_\downarrow)$ ~ 0.1, where $N_\uparrow$ and $N_\downarrow$ are the numbers of up and down spins respectively. However, very little is known about the nature of the B-phase.

To investigate the properties of the B-phase, we performed thermal conductivity κ_{xx} and thermal Hall conductivity κ_{xy} measurements on FeSe single crystals up to 20 T. Both quantities are very sensitive probes of the low-energy quasiparticle excitations in the superconducting state.

The field-dependence of the thermal Hall angle $\tan\Theta_H/B \equiv \kappa_{xy}/\kappa_{xx}^{qp}B$, which is proportional to the quasiparticle scattering time τ_{qp} (Fig. 2), shows a distinct kink at the boundary of the B-phase at H^*. Here κ_{xx}^{qp} is the quasiparticle thermal conductivity obtained by subtracting the phonon contribution κ_{xx}^{ph} from κ_{xx}. This indicates that the quasiparticle scattering mechanism is dramatically modified on entering the B-phase. Based on these results, we suggest that the B-phase is likely to a highly anomalous inhomogeneous superconducting state which has not been addressed before, rather than a conventional FFLO state [4].

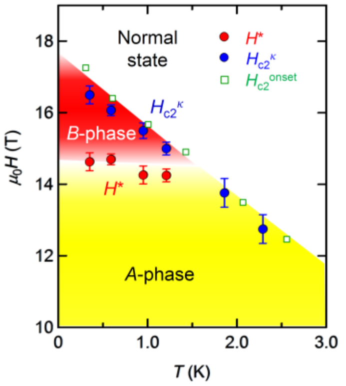


Fig. 1: H-T phase diagram of FeSe. The highly spin-imbalanced superconducting phase (B-phase) appears above H^* [1,4].

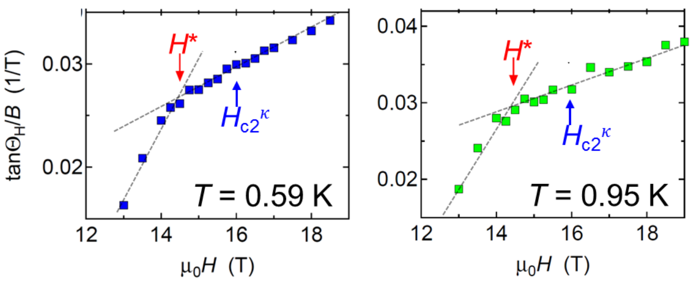


Fig. 2: Field dependence of the thermal Hall angle $\tan\Theta_H/B$ at T = 0.59 and 0.95 K. The clear kink anomalies appear on entering the B-phase at H^*.

References

[1] S. Kasahara and T. Watashige *et al.*, Proc. Nat. Aca. Sci. **111,** 16309-16313 (2014).
[2] T. Terashima *et al.*, Phys. Rev. B **90,** 144517 (2014).
[3] T. Watashige *et al.*, Phys. Rev. X **5,** 031022 (2015).
[4] T. Watashige *et al.*, submitted for publication.

Geometric Fluctuation Theorem

Advanced Statistical Dynamics Group　Kota Watanabe

Abstract We derive the current distribution and the fluctuation theorem for a geometric pumping under a periodic parameters change by using quantum Markovian master equation. As a result, we find absence of the reciprocal relation which is held for fluctuation in a steady current. We also verify the validity of our theory by Monte Carlo simulation in a spin boson system.

Steady current such as an electrical current or a heat current is a fundamental quantity to characterize the corresponding nonequilibrium phenomenon. There exists a steady current in the simplest setup where the bias such as the chemical potential difference or the temperature difference between reservoirs is constant in time. Such a steady current and its fluctuation can be derived by the current distribution. For example, a current distribution $P_\tau(J)$ during the time interval τ by applying a bias voltage V satisfies the steady fluctuation theorem

$$\lim_{\tau\to\infty} \ln\{P_\tau(J)/P_\tau(-J)\}/\tau = \beta eVJ ,$$

where β^{-1} is the temperature of reservoirs and e is the electrical charge. This fluctuation theorem give several kind relations such as the fluctuation dissipation between the conductance (dissipation) and noise power (fluctuation) or the reciprocal relation.

There exists different type current from a steady current, so called the geometric pumping current in a mesoscopic system. The geometric pumping whose origin is related to Berry-like phase [1] is realized by modulation of control parameters such as chemical potentials, gate voltages, and tunneling barriers. It is remarkable that there exists a net current without dc bias if there exists Berry-like phase.

In previous studies of the geometric pumping current, fluctuation theorems have not been systematically discussed, though e. g. we have discussed the non-adiabatic current in the geometric pumping process [2]. In this study, I have derived the current fluctuation theorem in a geometric pumping. My basic equation is the Markovian quantum master equation modified by the full counting statistics [3]. The current distribution is derived in the sufficiently small angular frequency Ω of parameters change. Then, the fluctuation theorem satisfies

$$\lim_{\tau_p\to\infty} \ln\{P_{\tau_p}(J)/P_\tau(-J)\}/\tau_p = A\Omega J + B\Omega J^3 + \cdots C\Omega^2 J + \cdots \mathrm{O}(\Omega^3) ,$$

where A, B and C depend on the path of modulation of parameters. In the case of sufficiently small Ω and J , this fluctuation theorem seems to be reduced to the similar equation in a steady current. Nevertheless, there exist some differences between our fluctuation theorem and the conventional one. In particular, there is no reciprocal relation in our case, though the fluctuation-dissipation relation is satisfied. I also verify the validity of our theoretical current distribution and the fluctuation theorem by the Monte Carlo simulation in a spin boson system.

References

[1] J. Ren, P. Hänggi and B. Li, Phys. Rev. Lett. **104**, 170601 (2010).
[2] K. L. Watanabe and H. Hayakawa, Prog. Theor. Exp. Phys. 2014, 113A01 (2014).
[3] M. Esposito, U. Harbola and S. Mukamel, Rev. Mod. Phys. **81**, 1665 (2009).