Wed01

Magnetic whirls and emergent monopoles in chiral magnets

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Small magnetic fields and thermal fluctuations stabilize lattices of magnetic whirls, so-called skyrmions, in chiral magnets. These skyrmions can be manipulated by very small current densities. The coupling of the electric currents to the magnetic structure is mostly governed by Berry phases picked up when the spin of the electrons adiabatically follows the magnetic textures. The effect of these Berry phases can be described by effective “emergent” electromagnetic fields. The topological quantization of the the skyrmions thereby leads to a quantization of the emergent flux, which also fixes the strength of the emergent electric fields when the skyrmions move [1].
A change of topology has to occur by singular magnetic configurations [2] which act as sources and sinks of the emergent magnetic flux. Thereby they can be viewed as emergent magnetic monopols.

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Wed02

Topological effects on magnetic excitations in magnetic materials

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Topological phenomena in condensed matter such as topological insulator has been attracting much attention. In this talk, we will discuss the two topics related to the topological effect on the magnetic excitations in magnetic materials.

The first topic is the magnetic excitations in skyrmion crystal. Quite recently, the crystallization of skyrmions, which are the topological magnetic textures with spin chirality, was found in chiral magnets such as MnSi and Cu_2OSeO_3. In this talk, we present the magnetic excitations in skyrmion crystal [1].We have found unusual magnetic excitations such as skyrmion rotation mode in skyrmion crystal.

The second topic in this talk is the Hall effect of magnons. The Berry phase of electrons in topological electronic state can be viewed as fictitious magnetic field and induces nontrivial Hall effect such as topological Hall effect in skyrmion crystals. The Berry phase induced Hall effect is also expected for charge neutral particles such as magnons. Recently, we have succeeded in observing the magnon Hall effect in terms of thermal transport [2]. The effect of the lattice geometry for the magnon Hall effect will also be discussed[3].

These works were done in collaboration with Y. Okamura, T. Ideue, H. Katsura, Y. Shiomi, S. Seki, S. Ishiwata, N. Nagaosa, and Y. Tokura.

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Transport Studies of Epitaxial Thin Films of Topological Crystalline Insulators

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The energy band inversion and time-reversal symmetry (TRS) are the main ingredients for realizing a nontrivial topology in Z_2 topological insulators (TI). Recently, the family of TIs has been extended by introducing the concept of topological crystalline insulators (TCI) where the topology is protected by a point-group symmetry of the crystal lattice rather than by TRS. The first material predicted to be a TCI was SnTe [1], in which the band inversion at an even number of time-reversal-invariant momenta leads to a trivial Z_2 topological invariant, but its mirror symmetry gives rise to a nontrivial mirror Chern number $n_M = -2$ to guarantee the existence of topologically protected gapless surface states (SS) on any surface containing a mirror plane.

Angle-resolved photoemission spectroscopy experiments have confirmed the existence of Dirac-like SSs on the (001) surface of SnTe [2], generating a lot of interest in this material. An important next step in studying TCIs is transport experiments. The challenge to probe SS in SnTe stems from a very high concentration of holes $\sim 10^{20} \div 10^{21}$ cm^{-3} and, thus, the total domination of the bulk conductance. Nevertheless, in SnTe grown as a thin film, an enhanced surface-to-bulk ratio and a high surface mobility expected for topologically protected SS might make it possible to probe surface Dirac quasiparticles in quantum oscillations.

In my talk I will show that high-quality SnTe thin films grown by molecular beam epitaxy on Bi_2Te_3 indeed possess desirable properties and allow to probe the topological SSs in transport experiments. The main observations are i) the coexistence of p- and n-type carriers deduced from the Hall measurements and ii) single-frequency Shubnikov-de Haas (SdH) oscillations measured in both $\rho_{xx}(B)$ and $\rho_{yx}(B)$. The dependence of the frequency of the SdH oscillations on the magnetic-field direction signifies that they stem from a two-dimensional (2D) Fermi surface. Furthermore, the phase of the oscillations indicates that the 2D carriers are Dirac electrons. Careful consideration of the energy-band diagram of grown SnTe/Bi_2Se_3 heterostructures makes it possible to conclude that the Dirac electrons reside on the top surface of SnTe. Those novel thin-film samples open new opportunities for experimentally exploring the physics of TCIs.

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Wed04

Berry curvature and topological phases for magnons

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Band structure for electrons gives rise to geometric structure of the Bloch wavefunctions in momentum space, characterized by the Berry curvature. The Berry curvature gives rise to various intrinsic Hall effects such as anomalous Hall effect and spin Hall effect. When the electronic bands have a gap and the system becomes insulating, the individual band separated from others by a band gap is characterized by a Chern number, which is an integral of the Berry curvature over the Brillouin zone. The Chern number is always an integer, and if it is nonzero, the system is in a quantum Hall phase, which is a topological phase with gapless chiral edge states.

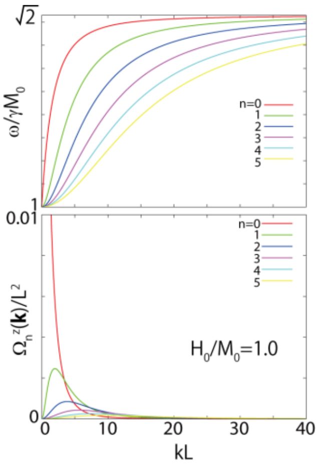

Fig.1: (a) Band dispersion and (b) Berry curvature for magnons in a ferromagnetic thin film.

In the similar manner, we can pursue analogous phenomena in magnons (spin waves) in magnets with dipolar interactions [1,2]. Dipolar interaction can be regarded as spin-orbit interaction for magnons, and it gives rise to nonzero Berry curvature. Indeed, in a simple case of ferromagnetic thin film with dipolar interaction in a perpendicular magnetic field, the Berry curvature can be calculated and shown to be nonzero (Fig.1). It leads to a thermal Hall effect of magnons[1,2].

Furthermore, when we introduce periodicity into magnet, the magnonic band structure may become gapped. In such magnonic crystals (MCs), we demonstrate that some magnonic bands can have nonzero Chern number, leading to chiral edge modes within the band gap. For the calculation we consider two MCs. One is a periodic structure of two ferromagnets arranged periodically (Fig.2(a)). In this case, as we make the unit cell size larger, the Chern number C_1 becomes nonzero (Fig.2(b)), and correspondingly there are chiral edge modes whose number is equal to the Chern number.

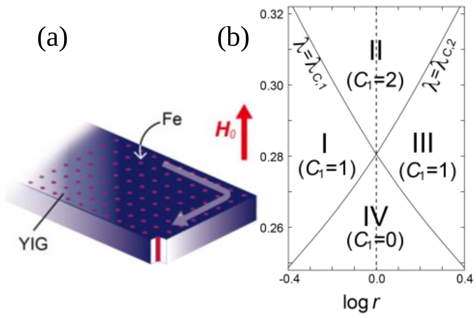

Fig.2: (a) Schematic of the MC, and (b) its phase diagram as a function of unit cell size [3].

The other MC considered consists of clusters, each of which comprises several magnetic dots [4]. In this MC, the magnonic levels within each cluster are calculated, and each magnonic level is regarded as an atomic orbitals such as *s*-orbital, p_x+ip_y-orbital, and so forth. In this way the whole MC can be seen as a tight-binding model consisting of the “atoms” (i.e. clusters) with several atomic orbitals, We can then see that in some cases the tight-binding model for this MC is identical with the model for quantum anomalous Hall effect of electrons, and the physical origin of the nonzero Chern number in this MC can be understood in the same way as that for electrons [4].

[This work has been done in collaboration with R. Matsumoto, R. Shindou, J. Ohe and E. Saitoh.]

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Wed05

Probing spin textures of topological surface states in ternary chalcogenides

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Three-dimensional topological insulators (3D TIs) with a gapless topological surface state (TSS) in a bulk energy gap induced by a strong spin-orbit coupling have attracted much attention as key materials to revolutionize current electronic devices. A spin helical texture of a TSS, where the electron spin is locked to its momentum, is a manifestation of a 3D TI.

A number of well-known thermoelectric and phase-change materials have so far been predicted to be 3D TIs. In order to experimentally confirm their topological natures, spin- and angle-resolved photoemission spectroscopy (SARPES) is one of the most powerful tools and it has actually been playing major roles in finding some real 3D TIs [1, 2]. Among the established 3D TIs, Bi_2Se_3 has been most extensively studied because of its relatively large energy gap and the simplest TSS. However, the topological surface state is energetically obscured by bulk continuum near and below the Dirac point, which is disadvantageous for spintoronic applications.

SARPES experiments were performed at the ESPRESSO end station attached to the APPLE-II type variable polarization undulator beam line (BL-9B) at Hiroshima Synchrotron Radiation Center (HSRC) [3]. The VLEED-type spin detector utilized in the ESPRESSO machine achieves a 100 times higher efficiency compared to that of conventional Mott-type spin detectors [2]. Photoelectron spin polarizations are measured by switching the direction of in-plane target magnetizations, thereby simultaneously eliminating the instrumental asymmetry, which is a great advantage for a quantitative spin analysis of nonmagnetic systems such as 3D TIs.

In this talk, some of the ternary 3D TIs such as $TlBiSe_2$ [4], $GeBi_2Te_4$ [5], Bi_2Te_2Se, and Bi_2Se_2Te [6] are shown to possess TSSs with marked spin polarizations. It has been revealed for $GeBi_2Te_4$ that a disorder in the crystal has a minor effect on the surface-state spin polarization, which is ~70% near the Dirac point in the bulk energy gap region (~ 180 meV). Highly spin-polarized features are also found for Bi_2Te_2Se and Bi_2Se_2Te, which are persistent across the Dirac point. The availability of both upper and lower TSSs promises to extend the variety of spintoronic application, for instance, to dual gate TI devices and topological p-n junctions.

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Wed06

Electromagnetic and Thermal responses in Topological Insulator and Superconductors

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Topological insulators are characterized by the bulk topological indices and gapless surface excitations which are connected to quantized responses of systems[1]. Topological superconductors and superfluids are superconductor analogues of topological insulators. We discuss nontrivial responses of topological superconductors and superfluids to the temperature gradient and rotation of the system. In two-dimensional gapped system, the Streda formula[2] for the electric Hall conductivity is generalized to the thermal Hall conductivity[3,6]. Applying this formula to the Majorana surface states of three-dimensional topological superconductors predicts cross-correlated responses between the orbital angular momentum and thermal polarization (entropy polarization). These results can be related to the gravitoelectromagnetism description of three-dimensional topological superconductors and superfluids[4,5,6], analogous to the topological magnetoelectric effect in $\boldsymbol{Z}_2$ topological insulators[1]. This work was done in collaboration with Akira Furusaki, Naoto Nagaosa, Shinsei Ryu.

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Wed07

Quantum phase transitions in correlated topological insulators

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We analyze the effect of the Hubbard interaction on a topological insulator (TI) by applying dynamical mean field theory to a generalized Bernevig-Hughes-Zhang model [1,2]. It is elucidated that the band inversion character of the TI leads to the large reduction of the spectral gap via the renormalization effect, resulting in the strong temperature-dependence of the spin Hall conductivity. We then extend our study to a magnetic phase transition, finding a topologically non-trivial antiferromagnetic (AF) insulator [3]. In particular, we uncover that this non-trivial AF phase is stabilized by electron correlations.

We further address a new intriguing phase "spin-selective topological Kondo insulator", which is a topological extension of the spin-selective Kondo insulator proposed for the ferromagnetic phase of the Kondo lattice model [4,5]. This phase demonstrates the stabilization of a correlated TI within a ferromagnetic metal phase.

We also investigate the proximity effects in a correlated heterostructure of a two-dimensional Mott insulator (MI) and a TI [6]. We show that the edge state of the TI induces strongly renormalized mid-gap states inside the MI region, which still have a remnant of the helical energy-spectrum. The penetration of low-energy electrons, which is controlled by the interface tunneling , largely enhances the electron mass inside the MI and splits a single Dirac-cone at edge sites into the spatially-separated two Dirac-cones.

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Antiferromagnetic topological insulator: model analysis and material design

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We formulate explicitly a scheme to achieve a novel topological state characterized by simultaneous finite charge and spin Chern numbers, based on the full control on the spin, valley and sublattice degrees of freedom of electrons in terms of a staggered electric potential, antiferromagnetic exchange field and spin-orbit coupling. With first principles calculation we demonstrate that the scheme can be realized by material modification in perovskite G-type antiferromagnetic insulators grown along (111) direction, where d electrons hop on a buckled honeycomb lattice and exhibit the Dirac behaviour. In a finite system, there appears a quantized edge current with full spin polarization, while the total magnetization is compensated to zero. Therefore, the material is a yeaned half-metallic antiferromagnet (HMAFM), with the additional merit that the spin-polarization of current can be inverted by the electric field, which is ideal for spintronics.

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Topological electromagnetic and thermal responses of time-reversal invariant superconductors and chiral-symmetric band insulators

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A fundamental and important feature of topological insulators (TIs) and topological superconductors (TSCs) is that topological invariants characterizing the bulk states emerge as physical quantities probed by electromagnetic or thermal responses. For instance, in the quantum Hall effect state, the Chern number appears as the quantized Hall conductivity, and in the case of time-reversal invariant (TRI) TIs in three dimensions, the Z_2 invariant can be detected in axion electromagnetic responses. However, in the case of chiral-symmetric systems in odd spatial dimensions, it has not been well understood how the bulk topological invariants can appear in electromagnetic and thermal responses. These classes include time-reversal symmetry broken (TRB) TIs with sublattice symmetry in one and three dimensions (class AIII), TRI TSCs in three dimension (class DIII, e.g. the B phase of He^3, $Cu_xBi_2Se_3$, Li_2Pt_3B), and TRI TIs and TSC of spinless fermions in one dimension (class BDI, e.g. Su-Schrieffer-Heeger model, Kitaev's Majorana chain model). For these systems, the bulk topological invariant is the winding number which takes any integer values. However, it has not been clear in what physical quantities the winding number can be detected. Here, we address this issue.

We clarify that the winding number which characterizes the bulk Z non-triviality of these systems can appear in electromagnetic and thermal responses in a certain class of heterostructure systems which consist of a topological insulator/superconductor and a trivial insulator/superconductor. Furthermore, we also elucidate that the winding number can be detected as a bulk response function for a novel magnetoelectric effect, i.e. "chiral charge polarization" induced by an applied magnetic field, which is a difference of charge polarization between two sub-lattices of chiral symmetric topological insulators.

Emergent phenomena in giant bulk Rashba semiconductors

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In this talk, I will overview our recent theoretical and experimental studies on giant bulk Rashba semiconductors. In these materials, the bulk electronic states exhibit extremely large Rashba spin splitting, due the strong spin-orbit interaction of electrons and the intrinsic bulk polarity of the systems. Backed by our first-principles calculations, we have experimentally observed this phenomenon in a group of Bismuth tellurohalides BiTeX (X=Cl, Br and I) [1,2]. I will briefly describe the electronic structure of these systems and further discuss the origin of giant bulk RSS based on the group theory and *k.p* formalism [3]. I will also show that as a result of giant bulk RSS, these materials exhibit a divergent orbital dia/para-magnetism, controllable by electron doping [4]. This effect is also shown to lead to some unique features in the optical conductivity [5] and magneto-optical response [6]. I will finally discuss the possibility to induce an unconventional topological phase transition in BiTeI under pressure [7,8].

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Search for Topological insulators in mixed valence compounds

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We propose the local density approximation Gutzwiller method incorporating a Green's function scheme to study the topological physics of correlated materials from the first principles. Applying this method to typical mixed valence materials SmB_6, we find its nontrivial Z_2 topology, indicating that SmB_6 is a strongly correlated topological insulator. The unique feature of this compound is that its surface states contain three Dirac cones in contrast to most known topological insulators.

Wed12

Recent progress on the first-principles analysis in heavy-electron systems

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Heavy-electron systems provide a unique playground to study novel quantum phases, such as complex magnetic / multipole order, unconventional superconductivity, and anomalous quantum criticality. In our understanding the microscopic origin of these interesting phenomena, the first-principles approach based on the density-functional theory (DFT) can provide key information about the electronic structure and the Fermi-surface topology. Recent progress like DFT + U method and DFT + DMFT (dynamical mean-field theory) offers us powerful tools to investigate the electron correlation effects. Quite recently, as a complementary method, we have successfully developed a procedure to evaluate several correlation functions based on the first-principles calculations [1]. This advanced approach clarifies complex magnetic / multipole fluctuations of itinerant f electrons based on the first-principles calculations. We here show the results in two famous heavy-electron compounds, URu_2Si_2 and $CeCu_2Si_2$.

First, URu_2Si_2 is a prominent example showing a novel electronic state below 17.5K [2,3], so-called hidden-order state [4]. In spite of every effort, the order parameter remains unknown. Recently, based on the above theoretical approach, we calculate the complete set of multipole correlations up to the fifth rank in the total angular momentum j=5/2 in f electrons. From the most divergent correlations, we find almost degenerate two states, the staggered ordered states of rank-1 dipole with A^{2-} and rank-5 dotriacontapole with E^- symmetry. These two states respectively correspond to the large-moment anti-ferromagnetic state observed under high pressures [5,6], and the hidden-order state. Our findings provide natural explanations of the key observations, including a nematic feature in the magnetic torque measurement [7].

Next, we discuss the superconducting gap symmetry in a first-discovered heavy-fermion superconductor $CeCu_2Si_2$ [8]. Although it has been widely believed to be a line-nodal d-wave superconductor driven by magnetic fluctuations, the electronic structure and the Fermi surface are not so clear yet. We here study the Fermi-surface topology and the corresponding multipole fluctuations based on the first-principles theoretical approach. We show that the DFT + U electronic structure indicates the presence of an electron sheet with heavy mass along X-P-X lines, and an incommensurate magnetic fluctuation develops remarkably due to the nesting, which is consistent with the neutron scattering measurement [9]. As expected, this magnetic fluctuation is compatible with the d_{x2-y2}-wave superconductivity. More interestingly, we find that a loop-nodal $s_{\pm}$-wave state is also a promising candidate comparably.

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Thu01

Phase diagram of the Kane-Mele Hubbard model

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In this talk I will review our present understanding of the phase diagram of the Hubbard model on the honeycomb lattice and in the presence of a spin-orbit coupling which leads to a non trivial topological band structure. By introducing magnetic pinning terms in the Hamiltonian, we can greatly improve our determination of the local moment. With this improved accuracy we will provide data which suggest that the transition from the semi-metal to the Mott insulating state is in the Gross-Neveu universality class [1]. In the presence of correlations, it is challenging to detect quantum spin-Hall (QSH) states. We will use magnetic π fluxes to achieve this goal and as a by-product provide a tool to build quantum spin systems within the bulk gap of topological insulators [2]. Our results are obtained on the basis of auxiliary field quantum Monte Carlo simulations which turn out to be free of the infamous minus sign problem for this class of Hamiltonians.

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Thu02

Effects of electron correlation on topological materials

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I review recent studies on interplay between electron Coulomb interaction and spin-orbit interaction. Possible emergence of topological phases induced by electron correlation in the absence of the spin-orbit interaction is also discussed.

One of the possible prominent electron correlation effect is generation of a topological insulator caused by the spontaneous symmetry breaking, arising from the Fock decoupling effect of the intersite Coulomb interaction [1]. An example of the extended Hubbard model on the pyrochlore lattice is discussed, where a realistic nearest-neighbor interaction stabilizes the topological “Mott” insulating phase [2]. The transition from a semimetal (zero-gap semiconductor) to the topological Mott phase shows unconventional quantum criticalities [3].

For the realistic value of the spin-orbit interaction as the model of $R_2Ir_2O_7$ with R being rare earth elements, the zero-gap semiconductors are expected to be realized, from which an all-in/all-out-type antiferromagnetic insulator emerges and Weyl fermions are proposed to generate an arc-like truncated Fermi surface on the sample surface [4]. In terms of realizing a two-dimensional metallic system with zero modes in a bulk insulator, the all-in/all-out-type antiferromagnetic insulator is shown to generate a two-dimensional Fermi surface confined in the magnetic domain wall, which is mapped to the protected ingap state of the one-dimensional Dirac equation with an analogy to the charge/spin solitons in polyacetylene [5].

Effects of Hubbard onsite interaction on Kane-Mele model incorporating the spin-orbit interaction on the honeycomb lattice have been studied extensively. I also examine a proposal for the possibility of strongly incoherent or insulating charge dynamics coexisting with the Tomonaga-Luttinger type spin liquid induced by the Coulomb correlation within the topological insulating phase in the bulk before the transition to the bulk Mott insulator [6].

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Peculiar superconductivity on $SrTiO_3$ surface induced by electric field-effect

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Electric field induced superconductivity has attracted considerable attention both in fundamental and applied physics. By fabricating field-effect transistor (FET) on a functional material, a two dimensional electron gas (2DEG) is formed on a surface of the material, and charge carrier density of the surface is electrostatically tuned by gate bias. We reported on high density carrier accumulation with an electric double layer transistor, which employs an electrolyte solution as a gate dielectric of FET. We firstly reported on superconductivity on two dimensional electron gas on an insulator $SrTiO_3$ single crystal [1], followed by a discovery of a new superconductor $KTaO_3$ by electric field-effect [2]. Electric field-effect tuning of superconductivity has been also reported on $(La,Sr)_2CuO_4$ and MoS_2. All of $KTaO_3$, $(La,Sr)_2CuO_4$ and MoS_2 has bell-shaped dependence of superconducting critical temperature T_c on gate bias, which is similar to a phase diagram of high-T_c cuprate and chemically doped $SrTiO_3$. In contrast, a 2DEG on $SrTiO_3$ has almost constant T_c with gate bias. We examined peculiar superconductivity on SrTiO3 induced by electric field effect.

First, we will show a precise phase diagram for $SrTiO_3$. Although electrolyte gating provides high density carrier doping, we cannot tune carrier density at low temperature where superconductivity emerges. This prevented a precise examination of phase diagram as a function of carrier density. We fabricated double gate device on SrTiO3, which has an top electrolyte gate and a back-gate electrode on the backside of the $SrTiO_3$ substrate. As $SrTiO_3$ has high dielectric constant at low temperature, transport properties are electrostatically tuned by the back gating below 1 K. We observed almost constant T_c of around 0.4 K for a sheet resistance R_S from 100 Ω to 10 kΩ, which is around the quantum resistance of h/e^2. In addition, critical current density J_c was rapidly decreased with increasing R_S and sheet resistance and decreasing a back-gate bias. J_c is fitted to be $R_S^{-1.5}$, which is similar to a relationship of $I_c \sim \Delta/R_S$ in a Josephson junction. This similarity suggests that 2DEG on $SrTiO_3$ is composed by a strong superconducting islands connected by weak superconducting (insulating) area, and charge carrier density is varied on the surface at around an insulating state.

Then, we will show two dimensional superconductivity on $SrTiO_3$. Since charge carriers are confined by an electric field in 2DEG, depth distribution of charges is changed with gate bias. However, it is not obvious whether thickness of a superconducting layer changes in similar manner. As a thickness of a thin film superconductor is deduced from anisotropy of critical magnetic field, we examined angular dependence of critical magnetic field for 2DEG of $SrTiO_3$ for various gate biases. We observed anisotropic critical magnetic field described by two dimensional Ginzburg–Landau equation. Thickness of superconducting layer remains nearly invariant, ranging from 11 nm to 13 nm, opposing to significant decrease of accumulation layer thickness from 20 nm to 4 nm with increasing V_G. This conflict also suggests peculiar superconductivity on $SrTiO_3$.

This work was conducted in collaboration with H. Aoki, Y. Iwasa, M. Kawasaki, N. Kimura, Y. Maeno, S. Nakamura, T. Nojima, A. Ohtomo, H. Shimotani, S. Yonezawa, H. T. Yuan.

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Thu04

Density Functional Theory for Plasmon-assisted Superconductivity

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Non-empirical calculation of superconducting transition temperature (T_c) has been one of the most fascinating challenges in condensed matter theory. Recently, density functional theory for superconductors (SCDFT) was formulated [1], and has been applied to various phonon-mediated superconductors. There, without introducing any adjustable parameters, the experimental T_c's were reproduced with Kelvin-scale accuracy.

In the conventional SCDFT, the screened Coulomb interaction has been treated within the static approximation, following the Migdal-Eliashberg theory. On the other hand, there have been theoretical proposals which exploit the dynamical structure of the screened Coulomb interaction [2,3]. For example, in doped band insulators, plasmons are expected to play a crucial role to lead strong pairing instability. Recently, we formulated a new scheme for plasmon-assisted superconductivity, and applied it to "high T_c" lithium under high pressure (T_c~20K). We found that plasmons significantly enhance T_c, and the agreement between theory and experiment becomes better [4].

This work was done in collaboration with Ryosuke Akashi.

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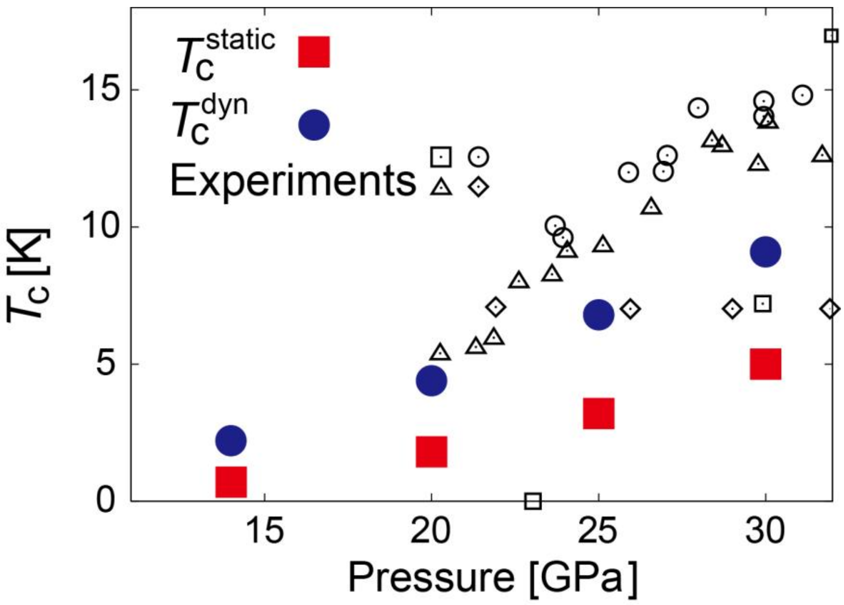

Comparison between the experimental and theoretical T_c. The T_c obtained by the present formalism (T_c^{dyn}) shows better agreement with the experiments than that by the conventional SCDFT (T_c^{static}).

Thu05

Vacuum engineering: Breakdown to topological control

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Using external forces, one can drive a many-body quantum state out from its equilibrium groundstate to some nonequilibrium excited state. This is a very old and fundamental problem in quantum physics that has its origin in the early development era of quantum field theory with two important progresses in the mid 1930s. In 1936, Heisenberg and Euler calculated the decay rate of the Dirac vacuum in strong electric fields using the effective Lagrangian method. The decay is caused by the pair creation of electrons and positrons, which is now known as the Schwinger mechanism. Another important observation was made in 1935 by Volkov who gave an exact solution to the Dirac equation in AC electric fields. These ideas also appeared in condensed matter with different names such as Zener breakdown, nonadiabatic Berry phase (Zak phase), and Floquet theory. Recently, such old ideas are being revived with new flavour added (Fig.).

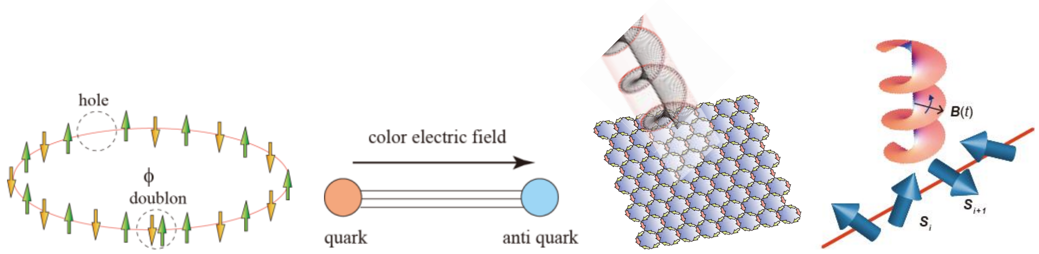

Fig. Various examples of "vacuum engineering": Mott insulator, QCD, Floquet topological phase transition, coherent control of quantum magnet.

Strong correlation (Mott insulator/Supersymmetric Yang-Mills)
Calculation of the groundstate decay rate (pair production rate) in strongly correlated systems is not easy. We found that this is possible in the one dimensional Hubbard model and N=4 Supersymmetric Yang-Mills theory, with the help of the Bethe ansatz + Landau-Dyhkne method [1] and holography [2]. In the latter case, a confinement/ deconfinement phase transition takes place when the field strength is stronger than the confinement force.

Topology (Floquet topological phase transition/ quantum magnet)
When circularly polarized electric field is applied to a two dimensional Dirac system (graphene, surface of TI etc.), a gap opens at the Dirac point and the system becomes a quantum Hall state [3,4,7]. This is the first example of the Floquet topological phase transition where one can show that Haldane's quantum anomalous Hall model [6] is effectively realized. Another phenomenon in this category takes place in quantum spin chains where topologically nontrivial phases can be realized. One can control these states using the magnetic component of laser [8,9].

* This is a work in collaboration with T. Kitagawa, K. Hashimoto, S. Takayoshi, M. Sato, L. Fu, E. Demler, A. Brataas, and H. Aoki.
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Thu06

Topological characterization of fractional quantum Hall ground states from microscopic Hamiltonians

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We show how to numerically calculate several quantities that characterize topological order starting from a microscopic fractional quantum Hall (FQH) Hamiltonian. To find the set of degenerate ground states (GS), we employ the infinite density matrix renormalization group (iDMRG) method based on the matrix-product state (MPS) representation of FQH states on an infinite cylinder. To study localized quasiparticles of a chosen topological charge, we use pairs of degenerate GSs as boundary conditions for the iDMRG. We then show that the wave function obtained on the infinite cylinder geometry can be adapted to a torus of arbitrary modular parameter, which allows us to explicitly calculate the non-Abelian Berry connection associated with the modular T-transformation. As a result, the quantum dimensions, topological spins, quasiparticle charges, chiral central charge, and Hall viscosity of the phase can be obtained using data contained entirely in the entanglement spectrum of an infinite cylinder.

Thu07

Symmetry Protected and Enriched Topological Phases

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Topological order, characterized by exotic quasiparticle statistics, gives a well established way of classifying gapped phases of matter in two dimensions, and falls outside the scope of Landau's symmetry-breaking classification paradigm. However, one can transcend Landau's classification even without resorting to phases with such exotic quasiparticles - in the presence of a symmetry group G there can exist so-called symmetry protected topological phases (SPTs) which have no anyons and no symmetry breaking but are nevertheless non-trivial. In this talk we discuss how to combine the two concepts to give a general classification of 2d topological phases with symmetries. In the process, we discover some seemingly allowed but physically inconsistent 2d theories, which find a natural physical interpretation as surfaces of 3d SPTs.

Thu08

Topological particle in magnets – Skyrmion –

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Particle is not a trivial concept in field theory. It is a lump with higher energy and momentum compared with those in the ground state. Therefore, a particle usually decays within a finite lifetime, and disappears. On the other hand, there are cases where the particle has a long lifetime due to the topological protection, i.e., it is characterized by a topological number which remains unchanged for the continuous deformation of the field configurations. Skyrmion in magnets is a representative example of this topological particle, which is found to be realized ubiquitously in helical magnets with DM spin-orbit interaction. Its motion is governed by the Berry phase and is different from the usual Newtonian particle, resulting in many novel phenomena. In this talk, I will discuss the dynamics of the Skyrmions and Skyrmion crystal driven by the external current and thermal fluctuation from the viewpoint of field theory and numerical simulation of LLG equation. It includes the current-velocity characteristics, impurity pinning effect, creation and annihilation by the current, thermal Brownian motion, and quenched dynamics.

Thu09

Theory of superconducting topological insulator

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Topological superconductor with time reversal symmetry is a hot topic now. Recently, topological superconducting state has been predicted in Cu doped Bi_2Se_3 ($Cu_xBi_2Se_3$)[1]. Point contact spectroscopy has shown a zero bias conductance peak (ZBCP) consistent with the presence of surface edge mode[2], i.e., surface Andreev bound states (SABSs)[2]. We study, i)Tunneling spectroscopy[3], ii)Josephson current[5], iii)Bulk properties[6] and relevant two-dimensional Rashba systems [7].

i)Tunneling spectroscopy of superconducting topological insulator [3]

We develop a theory of the tunneling spectroscopy for superconducting topological insulators (STIs), where the SABSs appear as helical Majorana fermions. Based on the symmetry and topological nature of parent topological insulators, we find that the SABSs in the STIs have a structural transition in the energy dispersions. The transition [3,4] results in a variety of Majorana fermions, by tuning the chemical potential and the effective mass of the energy band. We clarify that Majorana fermions in the vicinity of the transitions give rise to robust zero bias peaks in the tunneling conductance [2] between normal metal/STI junctions.

ii)Josephson effect of superconducting topological insulator [5]

We investigate the effect of helical Majorana fermions at the surface of superconducting topological insulators (STIs) on the Josephson current by referring to possible pairing states of Cu-doped Bi_2Se_3. The Josephson current-phase relation in an STI/*s*-wave superconductor junction shows robust $\sin(2\phi)$ owing to mirror symmetry, where ϕ denotes the macroscopic phase difference between the two superconductors. In contrast, the maximum Josephson current in an STI/STI junction exhibits a nonmonotonic temperature dependence depending on the relative spin helicity of the two surface states. Detecting these features qualifies as distinct experimental evidence for the identification of the helical Majorana fermion in STIs.

iii)Spin susceptibility[6]

We calculate the temperature dependence of the spin susceptibility for four promising superconducting pairings of a topological insulator Cu-doped Bi_2Se_3. We obtain wide variations of the temperature dependence of spin susceptibility for each pairing, reflecting the spin structure of the Cooper pair. We propose that the pairing symmetry of a superconducting topological insulator can be determined from measurement of the Knight shift by changing the direction of the applied magnetic field.

iv)Topological superconductor from bilayer Rashba systems [7]

We theoretically study a possible topological superconductivity in the interacting two layers of Rashba systems, which can be fabricated by the heterostructures of semiconductors and oxides. The hybridization, which induces the gap in the single particle dispersion, and the electron-electron interaction between the two layers leads to the novel phase diagram of the superconductivity. It is found that the topological superconductivity without breaking time-reversal symmetry is realized when (i) the Fermi energy is within the hybridization gap, and (ii) the interlayer interaction is repulsive.

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Fri01

How can we manipulate graphene --- chiral symmetry, topology and charged vacuum

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I shall give a theoretical overview of physics of graphene from a viewpoint of how the Dirac particle can be manipulated in terms of the chiral symmetry, topology and charged vacuum:
(i) While we know that the quantum Hall effect right at the Dirac point hallmarks the Dirac particle on the simple honeycomb lattice, we show how and why the zero-mode QHE is robust against various extensions (shifted cone, asymmetric cone, bilayer and tilted cone, etc; Fig.1), which is traced back to the "generalised chiral symmetry"[1,2]. When a disorder respects this symmetry, a criticality at the zero-energy Landau level is retained with an anomalous, fixed-point-like behaviour. Such manipulations (e.g., energy-resolved cones) have also implications on cold atom systems on optical lattices, where the controllability is greater than in electron systems.
(ii) Optical graphene Hall effect is interesting, where a plateau structure emerges in the Faraday rotation (Fig.2) as well in the relevant (THz) regime, as recently experimentally detected[3].
(iii) We finally propose how a "charged vacuum" can be realised when a dot is fabricated on a massive graphene[4]. The system then is analogous to the "supercritical nuclei" in atomic physics, and vacuum charging occurs as the bound levels plunge into the negative-energy continuum with the states exhibiting Fano-like resonance (Fig.3), which can be controlled by magnetic fields as low as 1 T, with experimental consequences.

The works described here are collaborations with Yasuhiro Hatsugai, Tohru Kawarabayashi, Takahiro Morimoto, Haruki Watanabe, Ryo Shimano, and Peter Maksym.

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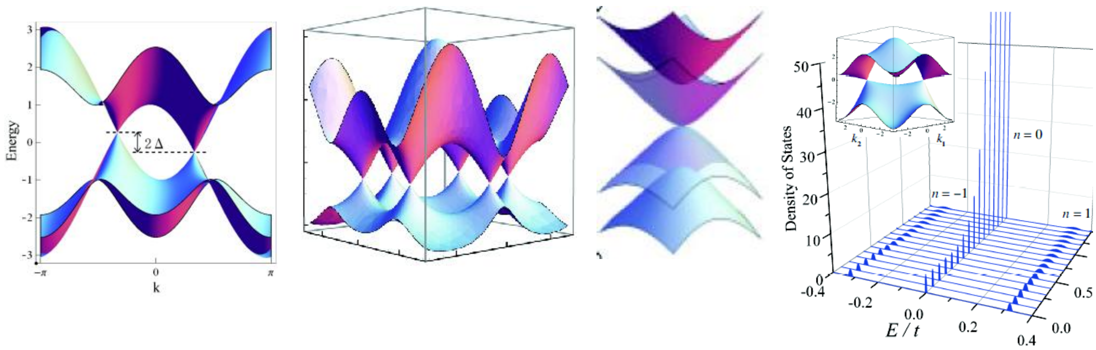

Fig. 1

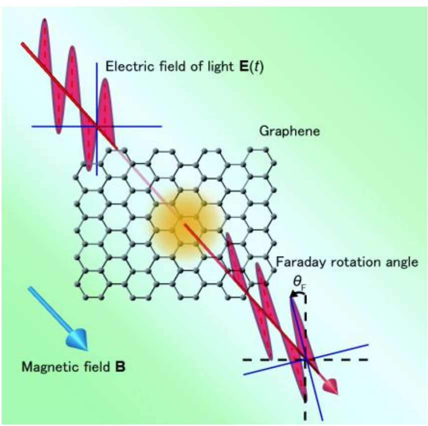

Fig. 2

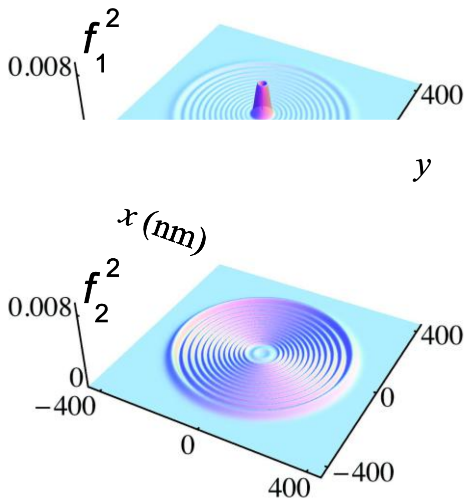

Fig. 3

Fri02

From Graphene to Silicene: Topological Phase Diagrams and Transitions

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Silicene is a monolayer of silicon atoms forming a two-dimensional honeycomb lattice. The low energy theory is described by Dirac electrons as in graphene, but they are massive. Remarkably the band gap of silicene can be controlled externally by tuning electric field [1], photo-irradiation [2] and antiferromagnetic order [3]. Silicene shows a rich variety of topological insulators such as a quantum spin-Hall insulator, a quantum anomalous Hall insulator [4] and a hybrid of them [3]. It also yields topological semimetals such as a single Dirac-cone state. The topological phase transition can be observed experimentally by measuring the optical absorption [5], orbital diamagnetism [6], the density of states and the conductance due to the gapless edge state [7]. We propose a field-effect topological quantum transistor with the use of the topologically protected zero-energy edge state of a silicene nanoribbon. This could be a basic component of future topological quantum devices. We report on the electronic properties of silicene superstructures[8], bilayer silicene[9] and silicon nanotubes[10]. We also analyze quantum Hall effects in various topological phases [11], where each phase is distinguished by Hofstadter's butterfly[12].

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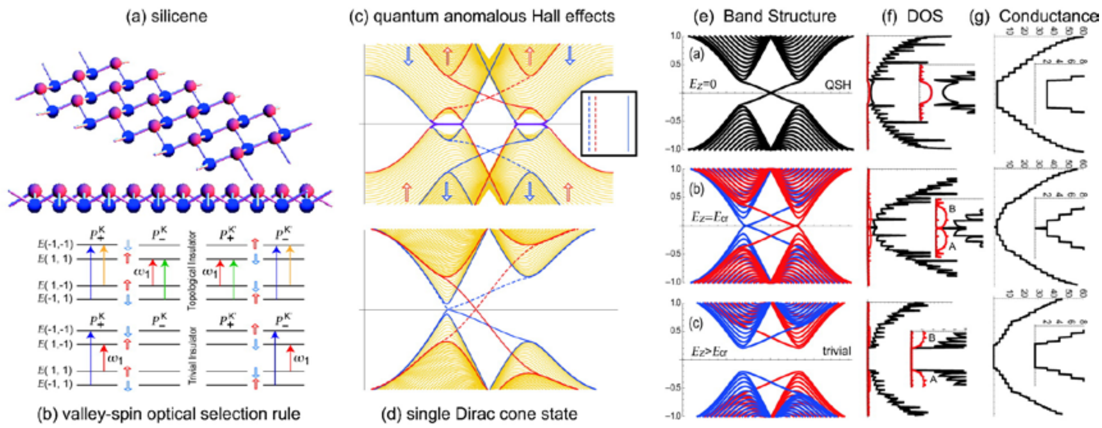

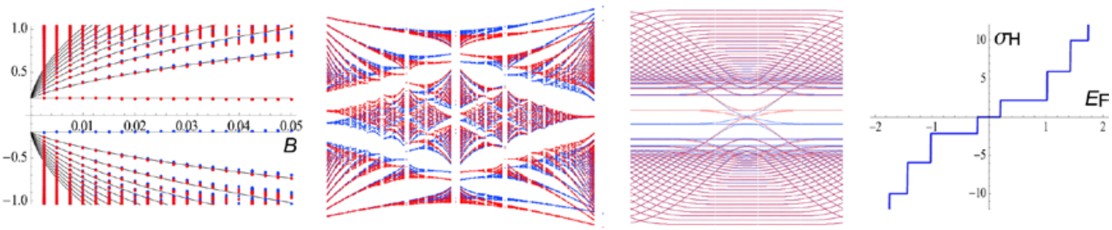

QHE fan diagram Hofstadter butterfly edge states Hall Conductivity

Fri03

Spin liquid phases in the SU(3) and SU(4) Heisenberg models on the honeycomb lattice

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SU(N) Heisenberg model is the effective model of Mott insulators with N degrees of freedom per site, when the interaction is highly symmetrical. Such a situation may happen for spin-orbital systems (when the crystal-field levels are partially filled) and for ultracold alkaline-earth atoms in optical lattices. Using a combination of analytical and numerical methods, such as flavor wave theory, infinite projected-entangled pair states (iPEPS), exact diagonalization, and Gutzwiller projected variational wave functions, we studied the zero temperature properties of the model on honeycomb lattice for different values of N.

For the SU(4) model, flavor-wave theory, tensor network algorithm, and exact diagonalizations find no signs of any form of lattice or SU(N) symmetry breaking. All properties, revealed by these methods, are very accurately accounted for by a projected variational wave function based on the π-flux state of fermions on the honeycomb lattice at 1/4 filling. In that state, correlations are algebraic because of the presence of a Dirac point at the Fermi level, suggesting that the symmetric Kugel-Khomskii model on the honeycomb lattice is an algebraic quantum spin-orbital liquid [1]. The algebraic liquid is stable against tetramerization, which occurs only for sufficiently large next nearest neighbor exchange [2].

Conflicting predictions have been made for the ground state of the SU(3) Heisenberg model on the honeycomb lattice: Tensor network simulations found a plaquette order [3], where singlets are formed on hexagons, while linear flavor-wave theory suggested a dimerized, color-ordered state [4]. A systematic study with iPEPS revealed that both competing states can be reproduced with iPEPS by using different unit cell sizes, and for sufficiently large tensor dimension it is the plaquette which becomes energetically favorable, thus the true ground state. The plaquette formation is also confirmed by exact diagonalizations and variational Monte Carlo studies, according to which both the dimerized and plaquette states are nonchiral flux states [5].

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Fri04

Conductance Tensors of Quantum Multiwire Junctions through Entanglement Renormalization

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We propose a method based on scale-invariant multiscale entanglement renormalization ansatz (MERA) to numerically extract the universal conductance tensor of an interacting quantum multiwire junction at the renormalization group (RG) fixed points. In contract to the DMRG method proposed previously, our method does not suffer from the finite-size effects. As an example, we will present our calculation of the conductance in a one-dimensional Luttinger liquid with a potential barrier (Kane and Fisher problem) and discuss different fixed-point behaviors for the attractive and repulsive interactions.

Study of elementary excitations of quantum spin liquid states in molecular-based materials

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Molecular-based organic compounds have a variety of choice for its components, enabling us to make fine controls of its band-width and its geometrical structures. One of the recent achievements done by the high degree of freedom of its material design is the discoveries of promising candidates for quantum spin liquids (QSLs) in the organic Mott insulators κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ and EtMe$_3$Sb[Pd(dmit)$_2$]$_2$ [1]. These materials have two-dimensional triangular lattice structure of spins with its spin interaction energy of J ~ 250 K. The NMR measurements have reported that there is no long-range order of spins down to ~20 mK (J/10,000), showing that a quantum disordered state is realized due to its geometrical frustration. In fact, magnetic long-range ordered states have been found at temperature of order of J for both compounds when the geometrical frustration is reduced by chemical substitutions. A central question about the putative quantum disordered states is how these QSLs are characterized, especially about the magnetic property of the elementary excitation and the phase diagram, i.e. whether the ground state is spin gapped or gapless and how it varies with frustration.

We've investigated the magnetic property of the elementary excitation of EtMe$_3$Sb[Pd(dmit)$_2$]$_2$ in which we've found mobile gapless excitations by the thermal conductivity measurements [2]. From highly sensitive magnetic torque measurements [3] down to very low temperature (30 mK) up to high field (32 T), we show that the QSL in EtMe$_3$Sb[Pd(dmit)$_2$]$_2$ in the zero-temperature limit presents a finite residual paramagnetic (i.e. Pauli) susceptibility, a hallmark of itinerant fermions in the Mott insulator. This residual susceptibility demonstrates the absence of spin gap, indicating that the ground state of this system is a gapless (algebraic) QSL where spin-spin correlations have anomalous (non-exponential) spatial dependence with infinite correlation length. Moreover, we study the frustration dependence of the elementary excitation in the mixed-cation materials (Me$_4$Sb)$_{1-x}$(EtMe$_3$Sb)$_x$[Pd(dmit)$_2$]$_2$ in which the degree of frustration is directly reduced by mixing the smaller cation. Magnetic torque measurements showed that spin susceptibilities of the mixed cation (x = 0.32 and 0.35) were temperature independent down to 30 mK and were almost the same with that of x = 1, indicating that the QSL exists as a quantum critical phase, rather than a point, when the frustration is varied. These results point toward the emergence of a quantum critical phase in which the spins of electrons remain mobile, despite the frozen charge degree of freedom.

I will also report a high-field torque measurement of κ-H$_3$(Cat-EDT-TTF)$_2$ which is recently found as a new candidate of QSL [4].

This work has been done in collaboration with D. Watanabe, Y. Senshu, S. Tonegawa, R. Okazaki, S. Kasahara, T. Shibauchi and Y. Matsuda at Kyoto University, T. Isono, A. Ueda and H. Mori at ISSP, Univ. of Tokyo, K. Ueda, H. Cui, Y. Oshima and R. Kato at Riken, I. Sheikin at CNRS (Grenoble), K. Behnia at LPEM(CNRS-UPMC), H.M. Yamamoto at IMS, and S. Uji and T. Terashima at NIMS.

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Fri06

Symmetry-protected topological phases of alkaline-earth ultra-cold fermionic atoms in one dimension

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Recent success in loading ultra-cold alkaline-earth fermionic atoms (e.g., ^{87}Sr, ^{171}Yb and ^{173}Yb) in optical lattices [1,2] has opened a new arena for the SU(N) (N=2I+1 with I being the nuclear spin) magnetism. The remarkable point is that the quenching of the electron angular momentum realizes SU(N) symmetry *without* any fine tuning of the parameters [3]. On top of this, there are two low-lying atomic states (the ground state $^1S_0$ and the metastable excited state $^3P_0$) and this necessitates to consider the two-band model.

In this talk, we discuss the phase diagram of the half-filled two-orbital SU(N)-symmetric Hubbard model in one dimension:

$$\begin{aligned} H_{\mathrm{G}} = &-t\sum_i \sum_{m=g,e}\sum_{\alpha=1}^{N}\left(c^{\dagger}_{m\alpha,\,i}c_{m\alpha,\,i+1}+\mathrm{h.c.}\right)-\mu_{\mathrm{G}}\sum_i n_i \\ &+\sum_i\sum_{m=g,e}\frac{U_{\mathrm{G}}}{2}n_{m,\,i}(n_{m,\,i}-1)+V_{\mathrm{G}}\sum_i n_{g,\,i}n_{e,\,i}+V^{e-g}_{\mathrm{ex}}\sum_{i,\alpha\beta}c^{\dagger}_{g\alpha,\,i}c^{\dagger}_{e\beta,\,i}c_{g\beta,\,i}c_{e\alpha,\,i}, \end{aligned}$$

where m=g, e denote the ground (g) and the metastable excited (e) states of each atom, and $c^{\dagger}_{m\alpha,i}$ creates the fermion with the nuclear spin I^z=$-I$,.., $+I$ and orbital m at site i. This is a model Hamiltonian of ultra-cold alkaline-earth fermions loaded into a one-dimensional optical lattice. Due to the interplay between the orbital and the SU(N) fluctuations, a very rich phase diagram is expected, which may be explored experimentally by exploiting great tunability of cold gases.

By using various methods (weak-coupling bosonization, density-matrix renormalization group, strong-coupling expansions, etc.), we found that the global topology of the phase diagram strongly depends on the parity of N (or, the value of nuclear spin I). For the simplest case N=2, we found four Mott-like phases as well as three density-wave-like phases [4]. For N=3, on the other hand, the Mott-like phases are replaced by gapless phases. For generic N=(even), we conclude that there is a new Mott-like featureless insulating phase, which may be viewed as a new kind of symmetry-protected topological phase, as well as the `orbital' Haldane phase found already in the N=2 case. This is in a stark contrast to the single-band case [6] where fully gapped phases always break translation symmetry for all commensurate fillings. Then, we discuss the properties of this new topological phase in detail paying particular attention to the emergent edge states, entanglement spectrum and the non-local string correlations.

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Fri07

Topological Phases of the Spin-1/2 Ferromagnetic-Antiferromagnetic Alternating Heisenberg Chain with Frustrated Next-Nearest-Neighbour Interaction

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The spin-1/2 ferromagnetic-antiferromagnetic alternating Heisenberg chain with ferromagnetic next-nearest-neighbour (NNN) interaction is investigated. The ground state is the Haldane phase for weak NNN interaction, and is the ferromagnetic phase for weak antiferromagnetic interaction.
We find a series of topologically distinct spin-gap phases with various magnitudes of edge spins for strong NNN interaction. The phase boundaries between these phases are determined on the basis of the DMRG calculation with additional spins that compensate the edge spins. It is found that the exact solutions with short-range antiferromagnetic correlation on the ferromagnetic-nonmagnetic phase boundary is representative of each spin gap phase.

Reference: K. Hida, K. Takano, and H. Suzuki: J. Phys. Soc. Jpn. in press; arXiv:1212.6012

Fri08

Designing permanent magnets from first-principles

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The attempts to develop new permanent magnets are highly interdisciplinary, the activities ranging from basic physics to actual implementations including metallurgy, synthesis, processing, and so on. In these efforts the role of electron theory of solid admittedly has not been in particular important so far. However, since the magnetism itself is a direct reflection of the quantum effects in electrons, we must say that the role of electron theory should be very important in developing permanent magnets. In this talk, the possibility of designing new permanent magnets on the basis of electron theory of solid will be discussed.

Since the study of permanent magnets definitely aims at their practical use, the theory should be quantitative as well as predictive. In this context the electron theory means the quantum design of materials: designing new materials on the basis of first-principles electronic structure calculation. As has been well recognized, state-of-the-art first- principles calculation provides rather accurate descriptions of the magnetic structure of crystals. However, this is still far from understanding permanent magnets. To better describe permanent magnets, quantitative discussion of magnetic anisotropy, coercivity, domain wall properties and its dynamics, and in addition, the finite temperature behaviors of all those quantities are indispensable. The efforts making coherent quantitative treatment of such properties of materials will be surveyed in the talk. As examples, the magnetic anisotropy of rare-earth nitride magnet $Sm_2Fe_{17}N_x$ and the possible application of an Fe-Cr antiferromagnetic layered structure as exchange bias for permanent magnets will be discussed.

Fri09

Quantum Fluctuations and Criticality in Pr based Spin Ice Systems

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Spin ice is a magnetic analog of H_2O ice that harbors dense static disorder. Dipolar interactions between classical spins yield a frozen frustrated state with residual configurational Pauling entropy and emergent magnetic monopolar quasiparticles. Introducing quantum fluctuations is of great interest as this could melt spin ice and allow coherent propagation of monopoles. Here, we report experimental evidence for quantum dynamics of magnetic monopolar quasiparticles in Pr based pyrochlore compounds, $Pr_2T_2O_7$. In the insulating $Pr_2Zr_2O_7$, we found >90% of the neutron scattering is inelastic and devoid of pinch points furnishing evidence for magnetic monopolar quantum fluctuations. On the other hand, the metallic $Pr_2Ir_2O_7$ exhibits a putative chiral spin liquid state, with strong non-Fermi liquid properties, suggesting the release of Pauling entropy due to quantum dynamics. This work is based on the collaboration with Kenta Kimura, Jun J. Ishikawa, Yo Machida, Collin Broholm, Jiajia Wen, Yoshi Tokiwa, Philipp Gegenwart, Hiroshi Sawa, Eiji Nishibori, Toshiro Sakakibara, Yasuyuki Shimura.

Fri10

Hydrodynamic theory for Coulomb and Higgs-confining phases in quantum spin ice

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Quantum spin ice is postulated as such variant of spin ice [1] that the spin-flipping exchange interaction [2] induces quantum dynamics of emergent magnetic monopole charge [3,4]. This is actually relevant to several magnetic pyrochlore oxides associated with rare-earth elements Yb [5,6], Pr [7-9], and Tb [10]. If we regard the macroscopically degenerate spin-ice ground-state manifold as a vacuum, this system can be described in terms of dilute interacting bosonic spinons that carry the monopole charge and are coupled to compact U(1) gauge fields [3,11,12]. Then, the quantum nature lifts the macroscopic degeneracy of the spin-ice manifold and yields a disordered ground state with deconfined spinons and linearly dispersive “photons” [3], as in the quantum electrodynamics in 3+1 dimensions. Strong enough exchange interaction drives this U(1) quantum spin liquid, or a quantum magnetic Coulomb liquid, into various ordered states with condensed monopolar spinons via the Higgs mechanism where gapless photons acquire an energy gap at a weakly first-order phase transition, forming a magnetic analogue of “superconductivity”. While a mean-field treatment of the emergent gauge field and spinon-spinon interaction can describe the ordered and disordered ground states properly [11,12], it breaks down at any finite temperatures where the gauge field can no longer be coherent over a certain finite length scale. It is intriguing to recognize, however, that the first-order transition accompanied by a Bose condensation of spinons continue from zero to finite temperatures. In particular, the Higgs mechanism for the zero-temperature transition [13] may effectively work if the transition to the Higgs phase occurs from the low-temperature quantum magnetic Coulomb liquid regime where the length scale for the gauge field is longer than that for spinons. Here, I present a hydrodynamic description of quantum spin ice at finite temperatures in terms of the associated quantum rotor coupled to spinons, and discuss Higgs-confining crossovers [13] of the spinon condensation phase and the transition separating it from the Coulomb phase, as well as a quantum-classical crossover of magnetic Coulomb liquids [14].

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Higgs transition from a magnetic Coulomb liquid to a ferromagnet in $Yb_2Ti_2O_7$

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Polarized neutron scattering experiments on $Yb_2Ti_2O_7$ crystal show that the diffuse [111]-rod scattering and pinch-point features, which develop on cooling are suddenly suppressed below T_C~0.21 K, where magnetic Bragg peaks and a full depolarization of the neutron spins are observed with thermal hysteresis, indicating a first-order ferromagnetic transition. Our results are explained on the basis of a quantum spin-ice model, whose high-temperature phase is effectively described as a magnetic Coulomb liquid, whereas the ground state shows a nearly collinear ferromagnetism with gapped spin excitations [1]. Systematically muSR experiments had been performed recently on ordered and disordered crystals and powder samples to investigate T, H-dependences. The H = 0 result on the powder almost reproduces Hodges's data [2]. Furthermore from the field dependence, we detected internal magnetic moments which are static in a muSR time scale.

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Quantum Spin Liquids, Density Matrix Renormalization Group, and Entanglement

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Recently, the density matrix renormalization group has become a tractable and powerful method for determining the ground states of two-dimensional quantum lattice models. Combined with conceptual advances from quantum information theory, this provides an unbiased method to diagnose and study quantum spin liquids in semi-realistic model Hamiltonians. In this talk, I will report upon our recent progress in this program.