Oral Sessions

Theory of spin current generation

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The collective magnetic excitation of spin, i.e., spin-wave (magnon), with momentum in a ferromagnetic insulator carries the spin current [1]. When the spin current is generated by the electric voltage via the spin Hall effect, it transmits the electric signal in the insulator [2]. When it is generated by heat, it carries the thermal energy, i.e., the Spin Seebeck effect [3,4]. Here, we formulate the spin current in a ferromagnetic insulator generated by various external forces based on the fluctuation-dissipation theorem [5]. The numerical simulation of spin current generation [6] is presented in a variety of nano-magnetic hybrids. A new paradigm in physics on spin current is discussed [7].

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Odd-frequency superconductivity induced by multi-channel Kondo effect

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Unconventional superconductivity has been sought as an intriguing ground state or thermodynamic state in condensed matter physics. Among those states, we address the odd-frequency (OF) pairing state, which breaks the gauge symmetry, but has a zero pairing amplitude at equal time [1,2]. Possible realizations of the OF superconductivity have been theoretically proposed in a variety of strongly correlated electron systems. In particular, Emery and Kivelson have shown for the two-channel Kondo impurity, where the localized spin couples to two degenerate conduction bands, that the OF pairing susceptibility is enhanced at the impurity site [3]. Motivated by their pioneering work, the possibility of the OF superconductivity has been discussed in the two-channel Kondo lattice [4,5] which is one of the basic models for Pr- or U-based heavy-electron systems. However, no microscopic theory has established the OF pairing in this system.

Recently, we have demonstrated the emergence of odd-frequency s-wave superconductivity in the two-channel Kondo lattice using the dynamical mean-field theory explicitly by divergence of the OF susceptibility [6]. The corresponding order parameter is given by a staggered composite-pair amplitude with even frequencies, which involves both localized spins and conduction electrons. The Kondo effect in the presence of two channels is essential for the present unconventional superconductivity. In the presentation, we will discuss the origin of ordering, and show physical quantities such as density of states and electrical resistivity. We will also propose a simple mean-field theory that describes this peculiar superconductivity. With use of the effective one-body Hamiltonian, it is demonstrated that the pairing state shows the ordinary Meissner effect.

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Spin Hall effect and large diamagnetism of Dirac electrons

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Spin Hall conductivity of fully relativistic Dirac electrons in a 4×4 matrix form is studied based on the Kubo formula aiming at possible application to bismuth and bismuth–antimony alloys.[1] It is found that there are two distinct contributions to spin Hall conductivity, one only from the states near the Fermi energy and the other from all the occupied states. The latter remains even in the insulating state, i.e., when the chemical potential lies in the band-gap, and turns to have the same dependences on the chemical potential as the orbital susceptibility (diamagnetism), a surprising fact. This effect comes purely from the inter-band effect, and it suggests a close relationship between the spin Hall effect and diamagnetism. These results are applied to bismuth–antimony alloys and the doping dependence of the spin Hall conductivity is proposed.

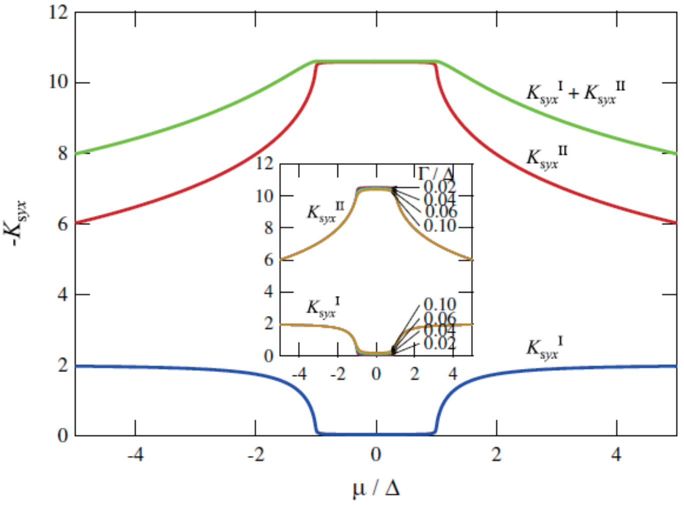

Fig. 1. Chemical potential dependence of the spin Hall conductivity. The inset shows the plot of K's for different damping rates. From Ref. [1].

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Renormalization of the Specific Heat Coefficient and the Density of States in the Interacting Fermion Systems

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It is one of the pivotal concepts of the condensed matter physics that the interaction will renormalize the quasiparticle mass of the Fermionic system and its typical consequence will show up as the enhanced Specific Heat (SH) coefficient γ - a well-known measure of the density of states (DOS) at the Fermi level. On the other hand, it can be trivially shown –although not well spread even in the community of expert researchers – that the density of states of the interacting fermion system is effectively unrenormalized by interaction. In this talk, I will reexamine how to reconcile the consistency relations among various transport coefficients of heavy fermion metals such as specific heat coefficient, thermal conductivity, etc, as well as Kadowaki-Wood relation.

Quantum criticality in iron-pnictide superconductors

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An enduring question in condensed matter physics is whether high transition temperature (T_c) superconductivity is driven by an underlying quantum critical point (QCP) separating different electronic phases at absolute zero-temperature. In particular, whether a QCP lies beneath the superconducting dome or the criticality is avoided by the transition to the superconducting state has been a central issue. We report a sharp depression of the superfluid density in very clean samples [1,2] of the iron-based superconductor, $BaFe_2(As_{1-x}P_x)_2$ that gives the first convincing signature of a second-order quantum phase transition deep inside the dome. We find that the x-dependence of London penetration depth exhibits a sharp peak at the optimum composition $x = 0.30$ ($T_c = 30$ K) [3]. This likely results from pronounced quantum fluctuations associated with the QCP which separates two distinct superconducting phases [4].

This work has been done in collaboration with K. Hashimoto, S. Kasahara, Y. Mizumaki, R. Katsumata, H. Ikeda, Y. Matsuda (Kyoto), K. Cho, M. A. Tanatar, R. Prozorov (Ames), H. Kitano (Aoyama-Gakuin), N. Salovich, R. W. Giannetta (Urbana-Champaign), and A. Carrington (Bristol).

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Exotic divergence of quadrupole susceptibility in an orbital order state

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In my talk, I review our recent theoretical work on exotic properties of orbital orders in the f-electron system $PrIr_2Zn_{20}$ [1]. In this compound, Pr ions on diamond sublattice have a non-Kramers doublet ground state, and they exhibit a phase transition at temperature 0.11K [2]. This transition is attributed to an antiferro order of quadrupole moments of those non-Kramers doublets [2,3]. Based on approximations including all the on-site fluctuations, we have identified various ordered phases in the temperature- magnetic field phase diagram. One interesting finding is unusually strong divergence of quadrupole susceptibility at the transition point. This is a consequence of bipartite cubic crystal structure, and this divergent behavior is generic to any antiferro quadrupole orders in cubic environment if the inter-site bond directions satisfy a condition.

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Localized States and Quantum Spin Hall Effect in Si-Doped InAs/GaSb Quantum Wells

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We study localized in-gap states and quantum spin Hall effect in Si-doped InAs/GaSb quantum wells. We propose a model describing donor and/or acceptor impurities to describe Si dopants. This model shows in-gap bound states and wide conductance plateau with the quantized value $2e^2/h$ in light dopant concentration, consistent with recent experiments by Du et al. We predict a conductance dip structure due to backward scattering in the region where the localization length ξ is comparable with the sample width L_y but much smaller than the sample length L_x.

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Correlation effects in artificially layered Kondo superlattices

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In recent years, it has become possible to produce artificial interfaces and hetero-structures of strongly correlated materials, opening a new field in material design. Quite recently artificially layered heavy fermion materials, such as $CeIn_3/LaIn_3$ and $CeCoIn_5/YbCoIn_5$ superlattices, have been created [1]. These materials are made of a periodic arrangement of heavy fermion layers and of normal-metal layers. Their intriguing properties seem to strongly depend on the number and arrangement of the different layers. We theoretically study such layered *f*-electron superlattices, and find a strong dependence of the paramagnetic state as well as the magnetic state on the superlattice structure [2]. The Kondo effect occurring in the *f*-electron layers manifests itself as resonances at the Fermi energy which change their shape depending on the layer. Furthermore, we analyze the dependence of the magnetic phase transition on the structure of the superlattice. These results demonstrate the possibilities of using artificial superlattices to tune the properties of strongly interacting materials.

We then apply the results to naturally layered *f*-electron materials like $CeCoIn_5$ [3]. Recent STM spectra taken on $CeCoIn_5$ surfaces [4] can be unambiguously explained by taking into account the influence of the layered structure on the appearance of the Kondo effect (Fig.1: the calculated STM spectra for a Co-terminated surface of $CeCoIn_5$). Our new scenario gives consistent theory of the STM spectra in contrast to the previous theoretical treatments which have failed to give consistent explanations.

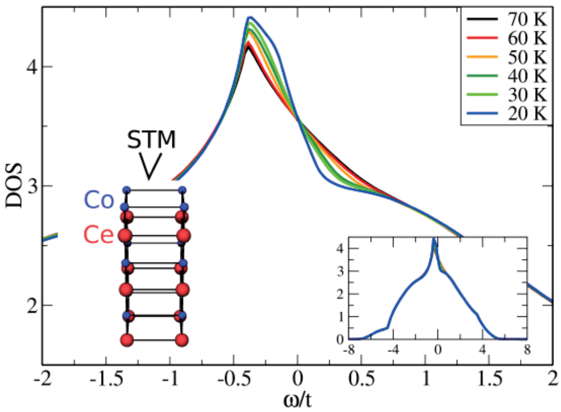

Fig.1: Computed STM spectra

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Inducing Correlated Spin Currents using BDI class Topological Superconductors

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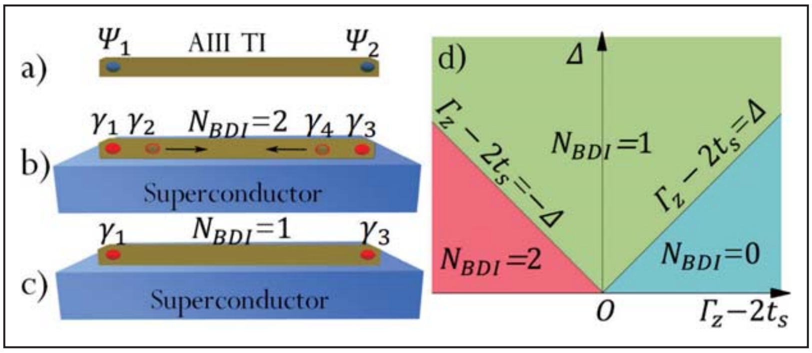
The study of the properties and applications of topological phases has been one of the most important subjects in condensed matter physics in recent years. Here [1] we show that inducing superconductivity on a AIII class topological insulator, which supports fermionic end states, results in a BDI class topological superconductor. The superconductor has two topological phases with one or two Majorana fermions (MFs) at each end of the wire. In the phase with two MFs and a normal lead is attached to each end of the superconductor, Cooper pairs from the superconductor can be efficiently split into the leads due to MF induced resonant crossed Andreev reflections. More importantly, the currents leaving the two normal leads are correlated and spin-polarized. This suggests that BDI class topological superconductors can be used as novel sources of correlated spin-polarized currents. These remarkable phenomena can be realized using quantum anomalous Hall insulators in proximity to superconductors.



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Theory of superconducting topological insulator

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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 develop a theory of the tunneling spectroscopy for superconducting topological insulators (STIs), where the SABSs appear as helical Majorana fermions. We find that the SABSs in the odd-parity 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 robust zero bias peaks in the tunneling conductance [3] between normal metal/STI junctions. We derive an analytical formula of the conductance of the present junction [6] which is an extension of the conductance formula of unconventional superconductors [7].

We study the effect of helical Majorana fermions at the surface of odd-parity STIs on the Josephson current. 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. 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.

We self-consistently study surface states and proximity effect. We demonstrate that, if a topologically trivial bulk s-wave pairing symmetry is realized, parity mixing of pair potential near the surface is anomalously enhanced by surface Dirac fermions, opening an additional surface gap larger than the bulk one. In contrast to classical s-wave superconductors, the resulting surface density of state hosts an extra coherent peak at the induced gap besides a conventional peak at the bulk gap but no such surface parity mixing is induced by Dirac fermions for topological odd-parity superconductors[8]. Our calculation suggests that the simple U-shaped scanning tunneling microscope spectrum does not originate from s-wave superconductivity of $Cu_xBi_2Se_3$.

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Stability of surface Dirac fermions against disorder

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A minimal model of topological insulators is a Dirac Hamiltonian. When a Dirac Hamiltonian has only a single mass term that is invariant under time-reversal transformation, the sign of the Dirac mass distinguishes topologically distinct insulators. The classification of topological insulators can thus be achieved by examining how many Dirac mass terms a Dirac Hamiltonian can have under symmetry constraint in a given dimension. This analysis can be systematically done using Clifford algebras [1]. I will review this approach (introduced by A. Kitaev) and then discuss stability (against disorder) of massless Dirac fermions on the surface of weak topological insulators [2] and/or topological crystalline insulators [3].

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Physics of J=1/2 State in 5d Transition Metal Oxides

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Since the J=1/2 state was first reported in Ir oxides [1] as a unique manifestation of the spin-orbit coupling (SOC) and on-site Coulomb interaction effect, there has been an enormous interest in 5d transition metal oxides as a candidate for exotic topological insulator and quantum magnet materials. In this talk we will discuss the role of electron correlation combined with strong SOC under a large crystal field, which is responsible for the observed J=1/2 state, and further an interesting competition between local lattice distortion and spin-orbit coupling, which controls the degree of J=1/2 components near the Fermi level. We investigate a possible topological quantum phase transition driven by the control of long-range hopping and trigonal crystal field [2]. In addition, we observe that intriguing effective magnetic interactions arise from the strong spin-orbit coupling with on-site Coulomb interaction. Possible topological insulator and exotic magnetic phases suggest that Ir-oxide and related systems can be an “interesting” playground for the study of the interplay between spin-orbit coupling and on-site Coulomb interaction.

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Ab initio molecular dynamics simulation of the electrode solution interface

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Chemical energy is efficiently converted to electricity at the electrode solution interface of a fuel cell. Despite the recent success in application to automobile and power plant, full understanding of the basic process remains a challenge of science. We have been studying the dynamics leading to the energy conversion using the density-functional molecular dynamics (DFMD) simulation. We will show detailed pictures on how the non-equilibrium bias potential applied to the interface yields the charge-transfer reaction, and vice versa, and how the platinum most efficiently prompts the energy conversion among other noble metals.

Our DFMD simulation provides reasonable explanation of the basic process, but one should be aware that the simulation is not truly quantitative yet. There are ambiguities originated from (1) microscopic modeling of the electrode potential, (2) treatment of the non-equilibrium nature of the electric double layer, (3) quantum nature of the nuclei, (4) quality of the potential energy surfaces. We show how those problems in fact reduce the accuracy of the present simulation, and thus how those problems need to be overcome. We emphasize, in particular, importance of accurate electronic structure calculation beyond the conventional density functional theory.

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Doublon diffusion in Mott insulators

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The nonequilibrium extension of inhomogeneous DMFT [1] has been implemented and used to study the photo-doping process and charge spreading in Mott insulating structures [2]. To a good approximation, the spreading of doublons and holes is diffusive and independent of the interaction strength. While the photo-excitation produces doublons and holes, pure electron doping via diffusion may be achieved in insulating heterostructures with suitably tuned gaps. We also apply the formalism to Mott insulating solar cells, where it is found that the separation of charge carriers by a strong potential gradient requires an efficient dissipation mechanism. The interaction with an antiferromagnetic background provides such a dissipation channel.

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First-principles study of the Mott transition and superconductivity in A_3C_{60}

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Doped fulleride superconductors A_3C_{60} (A=alkali metal), which exhibit a maximum transition temperature (T_c) of 40K, have attracted increasing attention in condensed matter physics. There, the energy scale of the band width, the Coulomb correlations, and the phonon frequencies are comparable, so that the validity of the standard Migdal Eliashberg theory has been questioned [1,2]. In fact, the superconducting phase resides in the vicinity of the Mott insulating phase.

In 2002, the emergence of phonon-driven superconductivity close to the Mott transition [strongly correlated superconductivity (SCS)] was proposed [3]. The key of this proposal is the presence of a weak phonon-driven attraction in the form of an *inverted* Hund's rule coupling, which is not renormalized by the strong short-range repulsion. However, the interacting parameters in the Hamiltonian are yet to be evaluated from first principles.

On the other hand, we recently develop an *ab initio* downfolding scheme, which we call "constrained density-functional perturbation theory (cDFPT)" [4], to derive the electron-phonon couplings and the phonon frequencies in the low-energy effective model. We estimate these parameters for C_{60} superconductors, for which the electron correlations are shown to be strong [5]. We show that the magnitude of the phonon-mediated exchange interaction is ~0.05 eV and that of the Coulomb exchange interaction is ~0.035 eV. Our result indicates that SCS is indeed realized in doped fulleride superconductors.

This work has been done in collaboration with Y. Nomura, S. Sakai (University of Tokyo), K. Nakamura (Kyushu Institute of Technology) and M. Capone (International School for Advanced Studies, Italy).

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Mott physics revealed in high temperature superconductors by resonant inelastic x-ray scattering experiments

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In recent resonant inelastic X-ray scattering (RIXS) experiments, energy dispersions of measured spin-wave or paramagnon excitations of cuprates show no signs of softening up to 40% hole doping or substantially hardening after only 15% electron doping. In this talk the anomalous result is explained by a simple explanation based one the t-J model. It reveals the presence of the strong correlation of Mott physics in highly doped cuprates. Some predictions will be also presented.

Symmetry Protected Topological Superfluids and Superconductors

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There have recently been intense interests in topological superconductors and superfluids. The A-phase and B-phase of superfluid ^{3}He are concrete examples of topological superfluids, where the former (latter) is categorized in terms of the time-reversa, particle-hole, and chiral symmetry to the class DIII (D) [1]. The non-trivial topological property ensures the existence of exotic quasiparticles, those are, Majorana fermions.

We here clarify the relation between symmetries and topology of superfluids and superconductors. In particular, we unveil that internal symmetry and crystalline symmetry may maintain the non-trivial topological properties even if the time-reversal symmetry explicitly breaks. By way of example, the topological superfluidity of ^{3}He-B is protected by the hidden $\boldsymbol{Z}_2$ symmetry originating from the discrete rotation of spin and orbital spaces [2,3]. This $\boldsymbol{Z}_2$ symmetry ensures non-trivial topological properties even in the presence of a time-reversal breaking perturbation. It is also demonstrated that the magnetic field induces the spontaneous breaking of the hidden $\boldsymbol{Z}_2$ symmetry, which is accompanied by the topological phase transition without bulk gap closing. We will also discuss the topological properties of superfluid ^{3}He-A [4], heavy-fermion superconductor UPt_3 [5], and spin-orbit coupled clod atoms [6]. Superfluid ^{3}He-A under a restricted geometry is found to be accompanied by non-Abelian Majorana fermions protected by the mirror Chern number. It is also demonstrated that UPt_3 under a magnetic field has multiple topological phases as a consequence of the mirror symmetry and the rotation of the $\boldsymbol{d}$-vector.

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The interface of $LaAlO_3/SrTiO_3$: Experimental clues

P.P. Aurino[1], Yu.A. Boikov[1,2], Yu Cao[1], T. Claeson[1], R.Gunnarsson[1], A. Kalabukhov[1], A. Klein[3], S. Li[3], L. Nyborg[1], E. Olsson[1], K. Rachut[3], V.I. Sakharov[2], I.T. Serenkov[2], N.Tuzla[1], M.P. Volkov[2], and D. Winkler[1]

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A thin, highly conducting sheet may form between the insulators $LaAlO_3$ and $SrTiO_3$. A critical thickness of epitaxial $LaAlO_3$ on a substrate of $SrTiO_3$ has to be exceeded in order to obtain a quasi-2DEG, and the conductance depends strongly on the oxygen pressure during deposition. At low deposition pressure, the conductance is due to oxygen vacancies; at high pressure, the interface may be insulating. Relatively high mobility can be obtained at intermediate oxygen pressure, the charge carrier density at the interface can be controlled by an electric field when $LaAlO_3$ is close to the critical thickness; it gives a possibility to control the superconducting transition temperature. Magnetic regions may coexist with superconducting ones. The behavior is often described as a transfer of free electrons from the free surface to the interface due to a polar effect. Our review will discuss how the conducting sheet may form also in other interfaces but $LaAlO_3/SrTiO_3$ and how it is influenced by thickness, oxygen background and annealing. Medium Energy Ion Spectroscopy, MEIS, indicates a substantial intermixing at the interface, more than seen by Transmission Electron Microscopy. Substantial intermixing is seen also for high-pressure $LaAlO_3/SrTiO_3$ as well as for a $LaMnO_3/SrTiO_3$ interface that are both not electrically conducting. Scanning Kelvin Probe Microscopy indicates inhomogeneity in the electron sheet of $LaAlO_3/SrTiO_3$ at low overlayer thickness. Irradiation by low energy Ar^+ ions may transform conducting parts (with thickness larger than the critical one) into insulating ones, enabling patterning of narrow paths without etching the film to under-critical thickness. High resolution TEM and XPS point upon a La/Al ratio higher than about 1 in irradiated, non-conducting regions, while it is less than unity in conducting ones.

High spin Fermi liquid

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Cold atomic gases offer us new opportunities to study quantum systems with higher spins. After briefly reviewing some earlier work, I shall focus on the recent systems of the alkaline and Ytterbium fermionic atoms with closed electronic shells, where the interaction is spin independent and thus obeys SU(N) symmetry, with N the number of components which can be as large as 10. I shall consider the Fermi liquid properties of this Fermi gas. After presenting the general formalism, the dilute repulsive gas would be considered, and I shall contrast the N=2 case with large N. Increasing N increases dramatically the fluctuations in this gas and can modify substantially the Fermi liquid properties. In particular, there is a large induced effective repulsive interaction between identical species and a suppressed spin-susceptibility. I shall also outline how these physical properties can be measured experimentally.

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How Maxwell's demon was exorcised: the minimum energy cost for measurement and erasure of information

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Abstract:

The second law of thermodynamics presupposes a clear-cut distinction between the controllable and uncontrollable degrees of freedom by means of macroscopic operations. The cutting-edge technologies in quantum information and nano-science seem to force us to abandon such a notion in favor of the distinction between the accessible and inaccessible degrees of freedom. In this talk, I will discuss the implications of this paradigm shift by focusing on how the second law of thermodynamics can be generalized in the presence of a feedback control [1]. I will also discuss the minimum work required for measurement and erasure of information [2]. The Jarzynski equality has to be generalized in the presence of feedback control [3], as confirmed experimentally using polystyrene beads [4]. I will also touch upon a fluctuation theorem which reflect the information exchange between a nonequilibrium system and other degrees of freedom such as an observer and a feedback controller [5]..

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Conversion between charge and spin currents by spin-orbit effects and examples of applications in spintronics

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Conversion between charge and spin currents can be achieved by using several types of spin-orbit (SO) effects, either SO effects specific of bulk materials, essentially the Spin Hall Effect (SHE), or SO effects at surfaces and interfaces, the Edelstein effect of Rashba states or similar effects for the surface states of topological insulators.

The SHE and the Inverse SHE (ISHE), large in heavy metals or metals doped with impurities of heavy elements, are today relatively well documented. I will simply summarize their main features and focus my lecture on interface SO effects. The Rashba coupling of surface or interface electron states has been extensively investigated by spectroscopic measurements, but how it can be exploited in spintronics is poorly known. Only a couple of experiments performed in semiconductor heterostructures have demonstrated the current-induced spin density predicted by Edelstein. I will present experiments of spin to charge conversion by the Bi/Ag Rashba interface which, at my knowledge, represent the first observation of the Inverse Edelstein Effect (IEE). Spin pumping is used to inject a spin current onto a Bi/Ag interface and the (large) charge current induced by IEE is clearly detected [1]. The theoretical modeling of the IEE has been recently presented in two publications [1-2]. I will mention how such experiments of spin to charge conversion can be extended to topological insulators.

The last part of the talk will be on the use of bulk and interface SO effects for the current-induced motion of domain walls (DW). Recent experiments have shown that large velocities can be obtained for the DW of magnetic films deposited on metals of large SO (i.e. Pt, Ta..). I will show how it can be explained by the combination of two SO effects: the stabilization of Néel DWs by SO-induced Dzyaloshinskii-Moriya interactions and the SHE-induced spin-torque [3]. In other configurations large velocities can also be obtained by using the Edelstein effect [4]. I will also compare the current-induced motion for DWs and magnetic skyrmions.

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Quantum transport in epitaxial Bi(111) thin films

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Quantum transport including the Aharonov-Bohm (AB) effect, universal conductance fluctuation (UCF), and weak anti-localization (WAL) have been investigated on epitaxial Bi thin films (10-70 bilayers) on Si(111). The results show that not only the top and the bottom but also the side surfaces of the Bi thin films are all robustly metallic as the film interior is always insulating. We propose that these properties are consistent with the existence of a topologically non-trivial thin film state where gapless states on all six surfaces are topologically protected. This is in sharp contrast with the known 2D topological states in a single bilayer Bi where only the four side edge states are topologically protected, as well as with bulk Bi where the surface states are believed to be not topologically protected.

Spin Seebeck Effect and Spin Heat Conveyer

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Spin current, a flow of spin angular momentum, is a key ingredient in spintronics. It plays an important role in giant and tunnel magnetoresistance [1], spin-transfer torque [2], as well as spin Hall effect [3]. Given such diverse needs of spin currents in spintronics, a lot of efforts are currently underway to establish efficient methods of generating, manipulating and controlling the spin current in solid-state devices. Here, we focus on the interplay of spin current and heat.

In the first part, we theoretically discuss the spin pumping driven by a temperature bias, i.e., the spin Seebeck effect [4,5,6]. The spin Seebeck effect enables the thermal injection of spin currents from a ferromagnet into an adjacent nonmagnetic metal, and most surprisingly, the signal is observed over a macroscopic scale of several millimeters. We present the linear-response approach to the spin Seebeck effect [7] and highlight the active role played by nonequilibrium magnons and phonons [8].

In the second part, we theoretically discuss a unidirectional heat flow that accompanies a non-reciprocal spin-wave spin current [9]. In this phenomenon, a special magnetostatic spin wave, the Damon-Eshbach mode at the surface of a ferromagnetic material, plays an important role, which propagates only in one direction specified by an applied magnetic field. This enables the direction-selective heat conveyer. We show that such a direction-selective heat flow arises as a result of the competition between heat diffusion by phonons and heat drift by the unidirectional spin wave.

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Quantum spin-liquid behavior in the spin-1/2 random Heisenberg antiferromagnet on the triangular lattice

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Experimental quest for the hypothetical “quantum spin liquid” state has recently met a few promising candidate materials including organic salts κ-$(ET)_2Cu_2(CN)_3$ [1] and $EtMe_3Sb[Pd(dmit)_2]_2$ [2], S =1/2 triangular-lattice Heisenberg antiferromagnets consisting of molecular dimers. These compounds exhibit no magnetic ordering nor the spin freezing down to very low temperature, while various physical quantities exhibit gapless behaviors. Recent dielectric measurements revealed the glassy dielectric response suggesting the random freezing of the electric polarization degrees of freedom.

Inspired by this observation, we propose as a minimal model of the observed quantum spin-liquid behavior the S =1/2 antiferromagnetic Heisenberg on the triangular lattice with a quenched randomness in the exchange interaction. We study both zero- and finite-temperature properties of the model by an exact diagonalization method [3], computing various physical quantities including the specific heat, the susceptibility, the antiferromagnetic Neel order parameter, the spin-glass-type order parameter, and the NMR longitudinal relaxation rate T_1^{-1}. We then find that when the randomness exceeds a critical value the model exhibits a quantum spin-liquid ground state. This randomness-induced quantum spin-liquid state exhibits gapless behaviors including the temperature-linear specific heat, and is argued to be a “random-singlet” or a “valence-bond-glass” state. The results provide a consistent explanation of the recent experimental observations not only on organic salts but also on inorganic compounds $Cs_2Cu(Br_{1-x}Cl_x)_4$ [4].

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Quantum spin ice

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Spin ice, with its magnetic monopole excitations, is perhaps the outstanding example an entropy-driven, classical, spin liquid. However the role of quantum effects in spin ice materials is relatively little understood, and the nature of their equilibrium ground state remains an open question. This question gains fresh urgency from recent experiments which suggest that the spin ice Dy2Ti2O7 may undergo a phase transition at low temperature [1], and from "quantum spin-ice" materials like Yb2TiO7, where quantum effects are expected to play a much larger role [2].

Here we explore how quantum tunnelling between different ice configurations changes the ground state phase diagram of a spin ice. We consider a model directly motivated by Dy2Ti2O7, in which long-range dipolar interactions, and competing second-neighbour exchange, are also taken into account. Using a combination of exact diagonalization and zero-temperature quantum Monte Carlo simulation, we offer compelling evidence for the existence of quantum spin-liquid phase with photon-like excitations [3,4]. We identify the competing ordered ground states, and establish that, a for realistic choice of parameters, only a small amount of quantum tunnelling is need to convert an ordered ground state into a quantum spin liquid.

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Intrinsic Angular Momentum and Edge States of Chiral Superfluids

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We consider the total angular momentum of a two-dimensional chiral superfluid confined in a rotationally invariant potential. When the superfluid is of chiral *p*-wave, for example, each Cooper pair has angular momentum 1. If we regard the system of N fermions as $N/2$ Cooper pairs, the total angular momentum would be $L=N/2$. On the other hand, Cooper pair formation may be only expected near the Fermi surface. This seems to imply that the total angular momentum L is strongly suppressed from $N/2$. These two conflicting pictures give a paradox, which has been debated for a long time. Although these studies led to much insight, the essential question has remained unsolved [1].

We attempt to clarify the issue by studying the ideal case of the spatially uniform gap function. We solve Bogoliubov-de Gennes equation explicitly, taking the existence of the conserved quantity $Q=L-\nu N/2$ [2], where ν is the angular momentum of each Cooper pair ($\nu=1$ for *p*-wave), into account. For the *p*-wave superfluid in a circular infinite well, we find that the angular momentum asymptotically approaches to $L\sim N/2$ in the thermodynamic limit with a fixed gap function. As in the case of most of the recent studies, this supports the picture that all the fermions participate in forming Cooper pairs.

On the other hand, surprisingly, for chiral superfluids of higher orders ($\nu>1$: *d, f,* … -wave) we find that the angular momentum is strongly suppressed from the maximum value of $\nu N/2$. The difference between *p*-wave and higher order ones is related to the structure of the edge states. We will also discuss a semi-classical approach to understand the difference.

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Driven Dirac system and gauge/gravity duality

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Quantum dynamics in correlated systems is becoming one of the hottest topics in theoretical physics. Dirac electrons realised in solid states show many exotic quantum phenomena. We study theoretically the nonequilibrium properties of 3D Dirac materials in electro-magnetic fields such as the production of electron-hole pairs via quantum tunneling, i.e., Schwinger mechanism (=Zener breakdown), as well as nonlinear optical responses. This is done by calculating the Euler-Heisenberg Lagrangian, which is the generating function of nonlinear optical response coefficients ([1] is a review). We also study the effect of correlation with a QCD-like toy model using gauge-gravity duality [2] and find universal relations that are accessible with solid state experiments.

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Even Denominator Fractional Quantum Hall Physics in ZnO

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We present our recent discovery of 3/2 and other fractional states with even denominator in an oxide heterostructure of MgZnO/ZnO (Fig. 1). In this system, the discontinuity in spontaneous electric polarization of polar crystals accumulates two-dimensional electron gas at the interface. Progress in thin film technology enabled us to attain a mobility over 700,000 cm^2/Vs [1]. Due to much large values of electron mass ($0.3m_0$) and spin susceptibility (g = 1.9) in ZnO compared with those in GaAs ($0.07m_0$ and −0.44), numbers of intriguing effects are realized. In the presentation, we describe that the strong correlation effect further enhances the g value to realize a cross-over of Zeeman and orbital energies, giving a birth of 3/2 state in this system.

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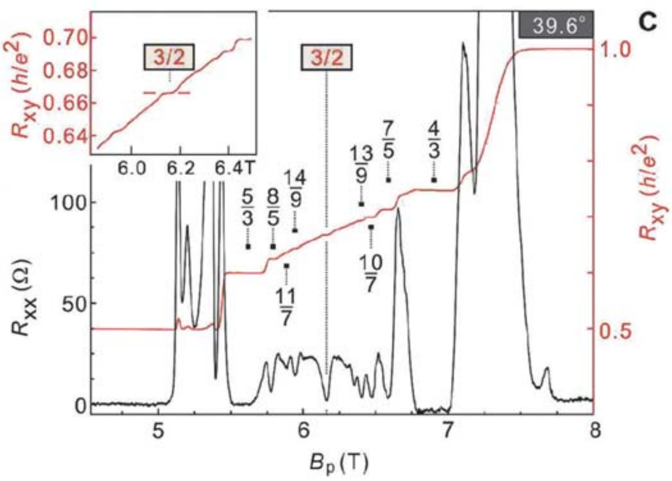

Figure 1 Magneto-transport of MgZnO/ZnO system in a tilted magnetic field.

Photoemission study of the role of the orbital angular momentum in the Rashba and Dresselhaus effects

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Orbital angular momentum (OAM), usually ignored in solids because of the OAM quenching, is found to play an important role in the determination of the electronic structure for a broad range of materials. First, it will be shown how one can detect OAM by using circular dichroism angle resolved photoemission (CD-ARPES). CD-ARPES is used to study surface states of various materials, including Bi_2Se_3.[1] The results reveal that not only spins but also OAM forms chiral structure, and the energy scale is determined by the interaction of asymmetric charge distribution and electric field. This result contradicts the conventional understanding of the Rashba effect.[2]

We expand our study to bulk states of III-V semiconductors with zinc blende structure for which inversion symmetry is broken. In spite of the weak atomic spin-orbit coupling, we observe strong CD-ARPES signal, indicating existence of fairly strong OAM. Existence of such strong OAM suggests that the energetics once again is greatly affected by the OAM. Moreover, heavy- and light-hole bands show different CD-ARPES patterns, implying that the dynamics that involve OAM are different in the two bands. We propose an effective Hamiltonian that is based on OAM.

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Topological phases in mix valence compounds

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In this talk, I will propose that the mix valence phenomena in some of the rare earth compounds will naturally lead to non-trivial topology in band structure.One of the typical example is SmB6, where the intermediate valence of Sm generates band inversion at the X point and the non-trivial Z2 index. Other than SmB6, YbB6 and YbB12 are both mix valence compounds. By applying LDA+Gutzwiller to these materials, we find that YbB6 has non-trivial Z2 index, indicating that YbB6 is another three-dimensional topological insulator with strong correlation effects. Our calculation also finds that YbB12 is a trivial insulator in the sense of Z2 but it can be classified as topological crystalline insulator with non-zero mirror Chern number. The electronic structure at finite temperature has also been studied using LDA+DMFT, indicating YbB6 is still in the mix valence region while YbB12 is quite close to the Kondo limit.

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Bad Metallic Transport in Model Hamiltonian Studies and in Transition Metal Oxides.

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We investigate the transport properties of a correlated metal within dynamical mean-field theory. Canonical Fermi liquid behavior emerges only below a very low temperature scale T_{FL}. Surprisingly the quasiparticle scattering rate follows a quadratic temperature dependence up to much higher temperatures and crosses over to saturated behavior around a temperature scale T_{sat} indicating the existence of “hidden” Fermi liquid behavior[1][2]. The non-Fermi-liquid transport above T_{FL}, in particular the linear-in-T resistivity, is shown to be a result of a strongly temperature dependent band dispersion. We derive simple expressions for the resistivity, Hall angle, thermoelectric power and Nernst coefficient in terms of a temperature dependent renormalized band structure and the quasiparticle scattering rate. We discuss the implications of the results for numerous transition metal oxides and other correlated materials connecting the non Fermi liquid transport with anomalous transfer of spectral weight.

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