A-14-1-1

Quantum Phenomena in ^{4}He Confined in Nano-porous Structures

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In Group A02 we study "Strongly correlated Super-clean Bose systems" realized by confining 4He (and H2) into various nano-porous materials. We search for new quantum phenomena, including quantum phase transition (QPT), Bose glass state and supersolidity, by performing thermodynamic and mechanical measurements.
We will discuss the following topics in this and the following talks, and in the poster session: (Parentheses indicate the main investigators for each study.)
(1) Heat capacity study of 4He in a 25 angstrom nano-porous glass (K. Yamamoto).
(2) Precise control of pore size by preplating of rare gas (Y. Shibayama).
(3) Search for quantum liquid state of H2 confined in nano-porous glasses (Y. Ishii).
(4) QPT-like behavior of 4He confined in one-dimensional pores (J. Taniguchi).
(5) Observation of "superfluidity" in solid 4He (M. Kondo).
(6) Simultaneous measurements of ultrasound and torsional oscillator for 4He in a nano-porous glass (T. Kobayashi).

A-14-1-2

Simultaneous Measurements of an Ultrasound and a Torsional Oscillator for ^{4}He in a Nano-porous Glass

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Recently, Yamamoto et al. have carried out torsional oscillator measurement for ^{4}He filled in a nano-porous glass containing 2.5 nm diameter pores (Gelsil). They reported a large suppression of superfluidity. The superfluid transition temperature T_C drops down to 1.4 K at zero pressure. Furthermore, it decreases monotonically with increasing pressure, and approaches zero temperature at a critical pressure P_C of 34 MPa. [K. Yamamoto, et al., *Phys. Rev. Lett.* **93**, 075302 (2004)] On the other hand, we carried out ultrasounic measurements and found that the pressure dependence of T_C and the temperature dependence of the superfluid fraction are very different from the torsional oscillator measurements. In order to clarify the origin of the difference, we have developed a new technique of simultaneous measurement of an ultrasound and a torsional oscillator, and the system successfully works for a nano-porous glass. Here, we report the comparison of decoupling of the superfluid component for between an ultrasound and a torsional oscillator.

A-14-1-3

^{4}He and ^{3}He Quantum Fluids Realized in *N* -Dimensional Nanopores

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We have been studying ^{4}He and ^{3}He adsorbed in various nanopores that have regular pore structures from three- to zero-dimensions [1]. Quantum fluid layers appear on the nanopores walls covered with about one atomic layer of inert or solid layers. In 1D nanopores of FSM, ^{4}He superfluid was observed for the pore diameter above 1.8nm [2]. Superfluid onset temperature in 1D 2.8nm pores is far below the temperature of the heat capacity anomaly that probably corresponds to the Gintzburg-Landau transition temperature. While, in 3D 2.7nm pores of HMM-2, superfluid onset and heat capacity anomaly (peak) occur at the same temperature, which is a character of the 3D long range ordering [3]. Boltzmann gas state of ^{3}He adatoms in the nanopores are realized by preplating the nanopores walls with ^{4}He layers [4]. In 1D nanopores, the ^{3}He gas at a low density shows a crossover from two- to one-dimension with decreasing temperature. Since the motion of a ^{3}He atom in the crossection of the 1D pore is likely to have discrete energy states, the 1D gas is realized at temperatures lower than the gap energy. Degenerate state of the 1D gas is suggested by a *T*-linear heat capacity at sufficiently low temperatures [5]. In the 3D 2.7nm nanopores, a Boltzmann gas of the adsorbed ^{3}He was suggested by a large molar specific heat of the order of the gas constant. Condition for the three-dimension, however, seems not to be theoretically established for the gas in the 3D nanopores.

[1] N. Wada *et al*., AIP Conf. Proc. **850** (2006) 289.
[2] H. Ikegami *et al*., submitted to Phys. Rev.
[3] R. Toda *et al.,* AIP Conf. Proc. **850** (2006) 285.
[4] T. Matsushita *et al.,* J. Low Temp. Phys. **138** (2005) 289.
[5] J. Taniguchi *et al*., Phys. Rev. Lett., **94** (2005) 065301.

A-14-1-4

Property of Surface Electrons on Rotating Superfluid ^{4}He

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Recent experiment on transport property of surface electrons (SE) on rotating superfluid ^{4}He showed that SE seemed promising experimental possibilities to study the detail of the surface with quantum vortex (QV) [1]. On the other hand, the experimental accuracy was not good for quantitative discussion in the previous experiment. Hence, we have done the same experiment using very stable rotating cryostat, which was constructed at RIKEN.

In the figure, the temperature dependence of the mobility (μ) above Wigner solid transition temperature for the $\Omega \leq 2$ rad/sec is shown. The μ was derived from the slope of the magneto-resistance (σ_{xx}) against B^2. The inset shows the Ω dependence of μ at 300 mK. The solid line in the inset was calculated on the assumption that the surface hollows induced by QV worked as an additional scattering center for transport property of SE. It is obviously that the μ(T,**Ω**) for the $\Omega \leq 2$ rad/sec has very slight **Ω** dependence and does not indicate any differences pronounced by previous experiment. We have also measured σ_{xx} (B) for $\Omega > 2$ rad/sec up to 5 rad/sec and the sliding phenomena of Wigner solid under rotation.

Any results indicated that the magneto-resistance of SE was not a proper probe to study the surface with QV. We report and discuss the detail of the experimental result.

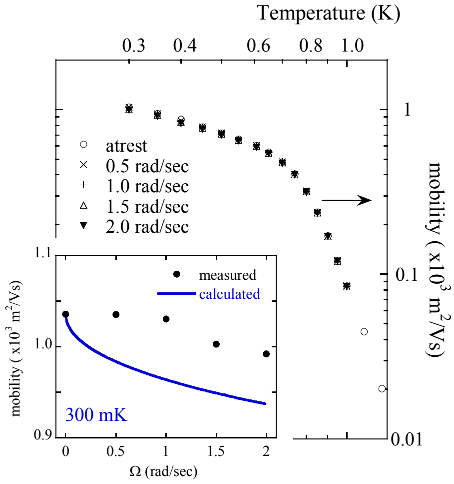

FIG.1: Temperature dependence of the mobility in the Ω below 2 rad/sec. Inset shows the Ω dependence of mobility at 300 mK. The detail is on

[1] H. Mukuda *et al.*, Physica E **18** (2003) 175.

A-14-2-1 **Theoretical discussion of Superconductivity in Materials without Inversion Symmetry**

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Unusual properties of the recently discovered heavy Fermion superconductor $CePt_3Si$ have motivated numerous experimental and theoretical studies [1,2]. Among the most intriguing experimental findings are the upper critical field exceeding the paramagnetic limit and aspects connected with the pairing symmetry. While the NMR $1/T_1$–data displaying a Hebel-Slichter peak indicate an enhancement due to coherence effects - a feature of conventional Cooper-pairing - several thermodynamic quantities evidencing power-law behavior are consistent with line nodes in the gap. The key to the understanding of these seemingly conflicting features lies in the antisymmetric spin-orbit coupling which is present due to the lack of inversion symmetry in $CePt_3Si$. This form of spin-orbit coupling lifts the spin degeneracy in a particular way and influences Cooper pairing dramatically. This is manifest in the fact that the standard classification in even/odd parity or spin singlet/triplet states obsolete.

A model calculation suggest that a pairing state belonging to the most symmetric representation of the generating point group C_{4v} can account for the observed phenomena. This state can be represented as a superposition of an s-wave and p-wave component (parity-mixing) and yields a gap with accidental line nodes while having a finite coherence factor, important for the interpretation of the NMR-data. The behavior of upper critical field can be in parts understood by the unusual renormalization of the spin susceptibility in the superconducting phase. In addition an intriguing new high-field phase, called helical phase can be induced for certain field directions. Further experimental probes to obtain information on the pairing symmetry and details of the gap function will be discussed. Moreover a number of new non-centrosymmetric superconductors such as $Li_2(Pd,Pt)_3B$, $CeRhSi_3$ and $CeInSi_3$ will be discussed in the light of the results obtained for $CePt_3Si$.

[1] E. Bauer, I. Bonalde and M. Sigrist, Low Temp. Phys. 31, 748 (2005).
[2] M. Sigrist, D.F. Agterberg, P.A. Frigeri, N. Hayashi, R.P. Kaur, A. Koga, I. Milat, K. Wakabayashi and Y. Yanase, Proceedings ICM Kyoto 2006.

A-14-2-2 **Magnetism and superconductivity in the ferromagnet UGe_2**

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UGe_2 is a ferromagnet with a Curie temperature T_{FM} = 52 K at ambient pressure. Interestingly, superconductivity appears within the ferromagnetic phase (see Fig.1) [1]. Subsequent researches have indicated that there exists a new line separating the ferromagnetic phase into FM1 and FM2, which possibly corresponds to the transition between fully polarized and partially polarized states [2]. The line terminates at a pressure referred to as P_X. Since a superconducting transition temperature exhibits a maximum at around P_X, it is likely that some fluctuation at around P_X induces the superconductivity [3]. According to our recent experiments [4], on the other hand, a (critical) point P_{FM} will also play an important role in the superconductivity. We will present the detailed *P*-*T* phase diagram and discuss the correlation between the ferromagnetism and the superconductivity.

[1] S. S. Saxena et al., Nature **406** (2000) 587.
[2] N. Aso et al., Phys. Rev. B **73** (2006) 054512.
[3] S. Watanabe and K. Miyake, J. Phys. Soc. Jpn. **71** (2002) 2489.
[4] S. Ban et al., presented at ICM'06, Kyoto.

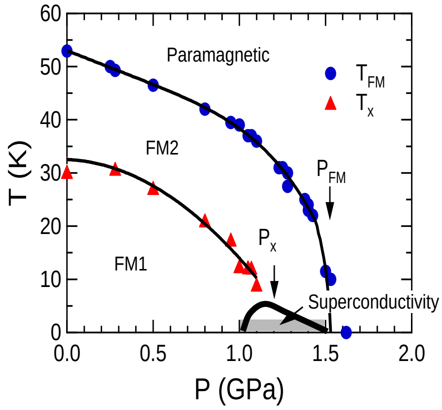

FIG.1: Pressure-temperature phase diagram of UGe_2. Two regions referred to as FM1 and FM2 are separated by a crossover or phase transition.

A-14-2-3

Measurements of Knight Shift and Spontaneous Field in Superconducting State of Sr_2RuO_4

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We have measured the Ru Knight shift in Sr_2RuO_4 at low magnetic fields in order to investigate the direction of the **d** vector in zero magnetic field. Ru NMR signal in small fields was observed by using nuclear-quadrupole-resonance (NQR) spectra. We have found that the Knight shifts along the c axis and the RuO_2 plane measured in a small field of ~ 500 Oe are invariant across T_c. These results suggest that the effect to fix the spins of the spin-triplet Cooper pairs is weak in Sr_2RuO_4, so that the spin direction is changed by the small magnetic fields applied for the Knight-shift measurements. We discuss possible interactions to fix the **d**-vector, which should be taken into account in Sr_2RuO_4.

We have also investigated the physical properties of the spontaneous field observed in the superconducting state. We performed μSR experiments on a Ru-Sr_2RuO_4 eutectic crystal, in which a superconducting precursor is observed immediately below 3 K. As shown in the main panel of the figure, the relaxation rate increases below the bulk superconducting transition temperature of about 1.5 K. Possible origin of the spontaneous field is discussed.

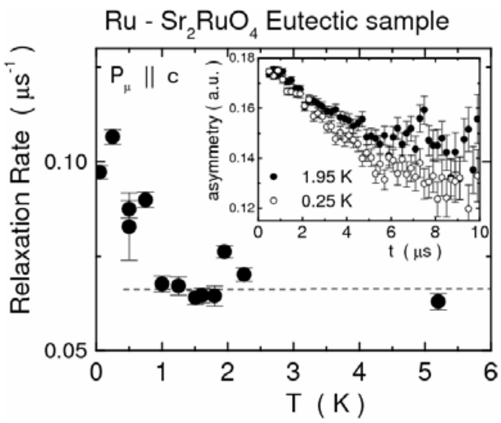

Fig.1: Temperature dependence of relaxation rate λ. The λ increases below the bulk transition temperature ~ 1.5 K. The inset shows the time dependence of the zero-field μSR decay at 1.95 and 0.25 K.

A-14-2-4

Magnetic properties in the normal and superconducting states in Sr_2RuO_4

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In the spin-triplet superconductor Sr_2RuO_4, the Knight shift in the NMR experiment does not decrease in any directions below the superconducting transition temperature (T_c). This indicates that the orientational energy of the order parameter field is less than energy corresponding to the applied magnetic field (*200G*). However, the anisotropy by the spin-orbit interaction estimated on the basis of the microscopic theory, and the dipole forces are of the order of *1kG*. This is inconsistent with the experimental data. Therefore, it requires a further investigation theoretically and exprimentally. In addition, the anisotropy of $1/T_1$ in the NQR experiment indicates that temperature dependence of the in-plane susceptibility is different from that of out-of-plane below T_c. On understanding the superconductivity in Sr_2RuO_4, it is important to clarify the magnetic properties.

Thus, we investigate the magnetic properties in the normal and superconducting states in Sr_2RuO_4 by extending the perturbative method into the spin triplet superconducting state. Considering the spin-orbit interaction, we discuss anisotropy of $1/T_1$, and the magnetic susceptibility.

A-14-2-5 Anisotropy of the Upper Critical Field in Sr_2RuO_4

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The layered ruthenate Sr_2RuO_4 has been attracting much interest because the spin-triplet superconductivity with ***d//z*** is inferred from several experimental facts[1]. The upper critical field H_{c2}, however, seems to be paramagnetically suppressed for the field perpendicular to the [001] direction at low temperatures, somewhat inconsistent with the above pairing scenario. It is worthwhile to inspect the magnetization in the superconducting state which reflects the paramagnetic effect. We have performed magnetization and magnetic torque measurements of Sr_2RuO_4 down to 0.1 K in the fields slightly tilted from the [001] plane.

Figure 1 shows temperature dependence of H_{c2} in the tilted field directions. Here θ is the angle between field and [001] directions. No paramagnetic suppression of the superconductivity is observed at $\theta > 5^\circ$ while the is strongly sup at $\theta \sim 3^\circ$. The H_{c2}-behaviors are discussed from the viewpoints o appearance of the high-field phase [2].

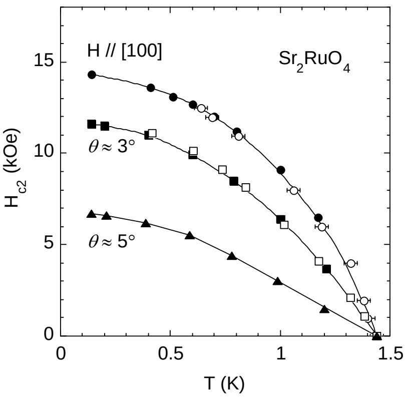

FIG. 1: Temperature dependence of H_{c2} in the various field directions

[1] K. Ishida *et al.*, Nature (London) **396** (1998) 658. [2]K. Deguchi *et al.*, J. Phys. Soc. Jpn. **71** (2002) 2839.

A-14-3-1 Superfluid ^{3}He in aerogel and in a narrow cylinder

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We report experimental results of superfluid ^{3}He in aerogel and in a narrow cylinder.

In aerogel the superfluidity of ^{3}He is largely suppressed by impurities of silica strands as a result of quasiparticle scattering by strands. The observed suppressed transition temperatures are well explained with the isotropic inhomogeneous scattering model above 1.0 Mpa (Fig.1). The A-like phase is observed at the very vicinity of the transition temperature down to the lowest pressure of 1.0 Mpa. The temperature width of A-like phase divided by the transition temperature is almost independent of pressure, that is quite different from bulk liquid. The phase conversion seems to occur from the central part of aerogel cylinder with cooling. We observed this phenomena with different aerogels in which the textures of A-like phase are different, one cell shows a positive frequency shift and another cell shows a negative shift.

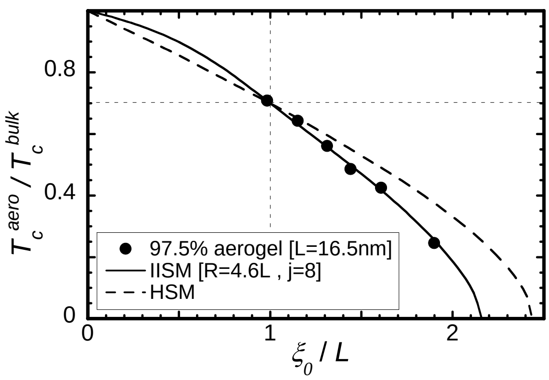

Fig. 1: The reduced superfluid transition temperature as a function of ξ_0/L.

We tried to observe an absorption signal of cw-NMR with only one narrow cylinder of 200 μm diameter at low frequency NMR and succeeded it. This will give us a possibility of measuring details of texture, vortex motion, gyro-magnetic effect and reconnection of vortices using the rotating cryostat at ISSP.

A-14-3-2 **Theoretical Study of Superfluid Helium-three in Aerogels**

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The main focus in the issue of superfluid 3He in aerogel is now to clarify the pairing symmetry of the equal-spin-paired A-like phase appearing close to Tc(P). We have previously clarified that the quenched disorder provided by the aerogel background stabilizes the ABM (axial) pairing state at the expense of destroying its genuine superfluid LRO and that a strong anisotropy of quasiparticle scattering via aerogel can stabilize not only the ABM but also the polar pairing states as a 3D phase [1]. To clarify which of these two mechanism is dominant to stabilize the A-like phase, we have first examined impurity effects on the strong-coupling (SC) correction and have found that impurity-induced diagrams overlooked so far lead to a significant reduction of the SC correction. It suggests a picture that, at high pressures, the ABM state is stabilized via the anisotropic scattering peculiar to the aerogel. Second, motivated by controversies [2] on interpretation of pulsed NMR frequency shifts, we have also examined the Leggett equations and found that not only the ABM but also the polar states can explain the nonnegative polsed NMR frequency shift.

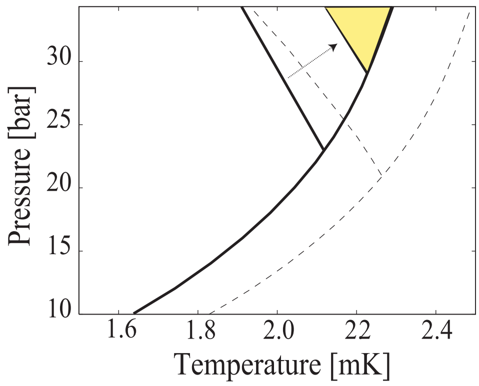

FIG.1: Resulting change of the mean field region of ABM state in the P-T phase diagram of impure liquid 3He. Thin solid curves are results in previous theories, while the dashes ones are those of bulk liquid.

[1] K.Aoyama and R.Ikeda, Phys. Rev. B 73, 060504(R) (2006). [2] G.E.Volovik, cond-mat/0605276,ver.8. .

A-14-3-3

Investigation of Phase Transition in Submicron Superfluid ^{3}He Film

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Superfluid ^{3}He film is the most advantageous super-clean material to understand boundary effects of unconventional superfluid/superconductor systems. Since the anisotropic *A* phase becomes more stable than the isotropic *B* phase because of a boundary effect in a thickness range of submicron, the *A*-*B* phase boundary is predicted as a function of the thickness. Recently, an inhomogeneous superfluid phase (stripe phase) was predicted in the *B* phase in the vicinity of the *A*-*B* phase boundary [1].

To investigate these characteristic phase transitions in superfluid ^{3}He film, we have measured the critical current J_c as the onset of dissipative flow over the thickness range from 0.3 to 4 μm using inter-digitated capacitors. In the thickness dependence of J_c, two distinct behaviors were observed at a thickness close to the predicted phase boundary of ~ 1 μm.

[1] A. B. Vorontsov and J. A. Sauls, cond. matt., (2006) 0601565

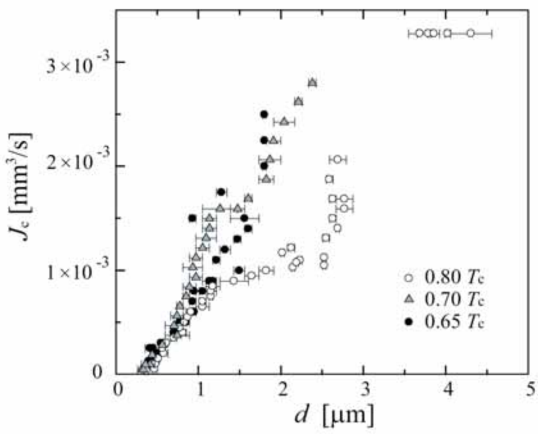

FIG.1: Thickness dependence of critical current. Averaged temperatures are denoted by legends. Two distinct behaviors were seen at a thickness of ~ 1 μm. In a thick film, different thickness dependences were seen and the scatters of results were larger than in the thin region.

A-14-3-4

Surface Enhancement of Spin Susceptibility in Superfluid ^{3}He-B

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It is known that p-wave pairing states show interesting behaviors near the surface.. When the p-wave order parameter has a component perpendicular to the surface, one finds surface bound states which have lower energies than the bulk energy gap. Since ^{3}He-B is the BW state which has three components, there occur inevitably surface bound states. Recently, we have shown that the pair excitation including the surface bound states dominates the temperature and the frequency dependence of the transverse acoustic impedance. Northwestern group also reported a specific heat data of ^{3}He-B in a restricted geometry which indicates the existence of surface bound states. In this report, we show that the spin susceptibility is also substantially enhanced by the presence of surface bound states. It exceeds the normal state Pauli susceptibility and is observable in superfluid ^{3}He-B film.

A-14-3-5 Visualization of Vortex Lattice in Rotating Superfluid ^{3}He-A

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We are developing a new rotating cryostat with high homogeneity and high field magnetic at Kyoto University to study quantum fluid dynamics of superfluid ^{3}He at ultra low temperature. One of our target using this machine is observation of vortex lattice of superfluid 3He-A phase with Ultra Low Temperature Magnetic Resonance Imaging (ULT-MRI) method. Core structure does not have cylindrical symmetry if it is the double core vortex and the triangular lattice is deformed due to the uni-axial symmetry of the A phase with superfluid flow predicted by Ohmi [1]. Distance between vortex cores is order of 100 μm at 6 rad/s and vortex core of superfluid ^{3}He-A phase is large as 10 μm because the core has non-singular. We improved resolution of our ULT-MRI from 25 μm × 25 μm to 6 μm × 6 μm. However, we still need improve the sensitivity because MRI expands NMR signals in frequency space. We are trying to improve the sensitivity of ULT-MRI with large magnetic field gradient and cryoamp with GaAs FET. We will report our situation of the new cryostat and improvement of ULT-MRI technique.

[1] T. Ohmi, JLTP **56**, 183 (1984)

A-14-4-1 Odd-frequency pairing state in superconducting junctions

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We present a general theory of the proximity effect in junctions between diffusive normal metals (DN) and unconventional superconductors in the framework of the quasiclassical Green's function formalism. Various possible symmetry classes in a superconductor are considered which are consistent with the Pauli principle: even-frequency spin-singlet even-parity (ESE) state, even-frequency spin-triplet odd-parity (ETO) state, odd-frequency spin-triplet even-parity (OTE) state and odd-frequency spin-singlet odd-parity (OSO) state. It is shown that the pair amplitude in a DN belongs respectively to an ESE, OTE, OTE and ESE. The generation of the OTE state in the DN attached to the ETO p-wave superconductor is of particular interest in the relevance to the novel proximity effect in Sr_2RuO_4 junctions.

We also studied about the ballistic normal metal / superconductor junctions for ESE and ETO state using the quasiclassical Green's function formalism. It is shown that the ESE (ETO) pair potential in a superconductor induces the OSO (ETO) pair amplitude in the absence of spin-flip scattering at the interface. The appearance of the midgap Andreev resonant states due to the sign change of the anisotropic pair potential at the interface is reinterpreted in terms of strong enhancement of the odd-frequency pair amplitude.

[1]Y. Tanaka et al, cond-mat/0609566, 0610017.

A-14-4-2 Josephson Spin Current in Triplet Superconductor Junctions

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We theoretically discusses the spin current in spin-triplet superconductor / insulator / spin-triplet superconductor (SIS) junctions as shown in Fig. 1(a). On the basis of the mean-field theory of superconductivity, the spin current is analytically calculated from the Andreev reflection coefficients of the SIS junctions [1]. At low temperatures, a midgap Andreev resonant state anomalously enhances not only the charge current but also the spin current. The coupling between the Cooper pairs and the electromagnetic fields leads to the Frounhofer pattern in the direct current spin flow in magnetic fields and the alternative spin current under applied bias-voltages. To generate the spin current, we also propose a bending SIS junction of the spin-triplet superconductor Sr_2RuO_4 [2]. A part of this work will be given in Ref. [3].

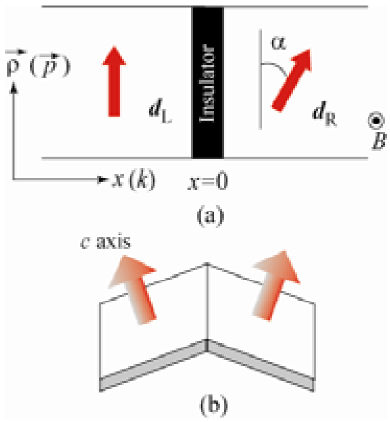

FIG 1: Schematic picture of a SIS junction.

[1] Y. Asano, Phys. Rev B **72**, 092508 (2005).
[2] Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J. G. Bednorz, and F. Lichtenberg, Nature **372**, 532 (1994).
[3] Y. Asano, Submitted to Phys Rev.B, cond-mat/0610029.

A-14-4-3 Spin-Triplet Superconductivity and Excitation Spectra in the Two-Chain Hubbard Models

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We calculate the spin and charge excitation spectra of the two-chain zigzag-bond Hubbard model at quarter filling in order to seek for consequences of the spin-triplet pairing induced by the ring-exchange mechanism [1,2]. The model is topologically equivalent to the one-dimensional (1D) Hubbard model with nearest-neighbor t (>0) and next-nearest-neighbor t' (>0) hopping integrals, whereby we consider the case at $t << t'$. We use the dynamical density-matrix renormalization group (DMRG) technique to calculate the excitation spectra. Confirming the accuracy of our method by reproducing the spectra in the noninteracting systems, we investigate how the spectra are deformed when the strong onsite Coulomb interaction U sets in. We find that the spin and charge excitation spectra are basically the same as those of the 1D Hubbard (and t-J) chain at quarter filling, where the spectra come from the two nearly independent 1D chains along the hopping integral t'. However, we find that the hopping integral t plays a crucial role in the short-range spin and charge correlations; i.e., the ferromagnetic spin correlations between electrons on the neighboring sites is enhanced and the spin-triplet pairing correlations between the electrons is induced, of which the consequences are clearly seen in the calculated spin and charge excitation spectra at low energies. Relating two-chain Hubbard models and their possible pairing states are also considered.

[1] Y. Ohta, S. Nishimoto, T. Shirakawa, and Y. Yamaguchi, Phys. Rev. B **72**, 012503 (2005).
[2] S. Nishimoto, T. Shirakawa, and Y. Ohta, in preparation.

A-14-4-4

Superconductor as Doped Mott Insulator in 2D Hubbard Model

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[2]*Department of Engneering, Chiba Institute of Technology, Shibazono, Narashino 275-0023*
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At half filling (n=1, n: electron density), an (antiferromagnetic or paramagnetic) insulating phase is considered to be predominant in the 2D Hubbard model. Recently, we studied the mechanism of paramagnetic Mott transition occurring at $U=U_c\sim W$ (W: band width) on the square lattice with diagonal hopping t', using an optimization variational Monte Carlo method [1]. The essence of the transition is binding and unbinding of a doublon to a holon. In a narrow range of U immediately below U_c, robust superconductivity (SC) appears, although this SC is actually hidden by antiferromagnetism (AF). In the insulating side ($U>U_c$), SC is completely suppressed.

We extend this study to the case of $n<1$ but $n\sim 1$, where AF is suppressed owing to the broken nesting condition, and the present model becomes a plausible model of high-T_c cuprates. Here, doublon-holon binding is still important to form a SC pair. We have found following properties:

1. As soon as n goes away from half filling, the range of SC extends to $U\to\infty$.
2. Like the case of n=1, SC is negligibly small for weakly-correlated regime ($U/t<4$).
3. A Mott transition at half filling changes to a crossover of the mechanism of SC from a BCS (weak-correlation) type to an unconventional strong-correlation type.
4. For $U<U_c$, a SC correlation function is basically a decreasing function of doping rate, δ (=1-n), whereas for $U>U_c$, a SC correlation function has a maximum at $\delta\sim 0.15$, as the cuprates do.

Hence, the high-T_c cuprates should have larger U than U_c. We will address some related topics.

[1] H. Yokoyama *et al*., J. Phys. Soc. Jpn. **75** (2006) vol. 11.

A-15-1-1 Quantum Turbulence ～Another Da Vinci Code～

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About 500 years ago Leonard Da Vinci observed turbulent flow of water and drew a sketch showing that turbulence consisted of lots of vortices. "Another Da Vinci Code" of this sketch may give a key issue for understanding turbulence, while it is not so clear to know the relation between turbulence and vortices in a classical case. On the other hand, quantum turbulence (QT) comprises a tangle of quantized vortices which are stable topological defects, being expected to give a prototype much simpler than classical turbulence (CT); "Another Da Vinci Code" is realized in QT, rather than CT. After discussing the recent motivation of this field, I will review the latest activity of our group on QT.

(1) We showed that the energy spectrum of QT obeys the Kolmogorov law that is the most important statistical law in turbulence, by the numerical analysis of the Gross-Pitaevskii (GP) equation [1]. The analysis of the coupled system of the GP and the Bogoliubov-de Gennes equations found the mutual friction of quantum turbulence in dilute Bose condensates at finite temperatures [2].

(2) As a transient state when a seed vortex expands to the full volume under rotation, we discovered "Twisted vortex state" [3].

(3) Concerned with the recent experiments on QT created by vibrating structures, we found numerically the transition to QT near structures under the AC superflow [4].

[1] M. Kobayashi and M. Tsubota, Phys. Rev. Lett.. **94** (2005) 065302.

[2] M. Kobayashi and M. Tsubota, Phys. Rev. Lett., **97**(2006) 145301.

[3] V. B. Eltsov, A.P. Finne, R.Hanninen, J.Kopu, M. Krusius, M.Tsubota, E.V.Thuneberg, Phys. Rev. Lett., **96** (2006) 215302 .

[4] R. Hanninen, M. Tsubota and W. F. Vinen, cond-mat/0610224. .

A-15-1-2
Generation of Quantum Turbulence by a Vibrating Wire in Superfluid ^{4}He

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We investigated the motions of quantized vortices attached to a boundary and the generation of quantum turbulence by using a vibrating wire in superfluid ^{4}He. The velocity of the wire grows in the potential flow regime with increasing drive force, until attached vortices unstably expand by superfluid currents relatively generated, causing turbulence. The resonance frequency of the vibrating wire in superfluid suggests that the attached vortices form a layer on the wire, even for low velocity currents. In turbulence, chaotic motions of vortices such as entanglement and reconnection reduce the thickness of the layer in spite of the fact that the vortices unstably expand. When the turbulence subsides, the wire velocity increases to high values in the potential flow regime, as shown in Fig. 1. The temperature dependences of velocities before and after the change of the flow suggest that the thermal excitations affect the motions of quantized vortices.

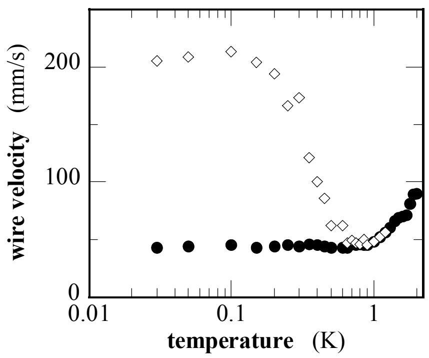

FIG.1: Temperature dependence of velocities of a vibrating wire for which the flow state changes. The solid circles show the critical velocity at which the turbulent flow disappears. The open circles show the maximum velocity in the potential flow

A-15-1-3

Millimeter-wave Spectroscopy of the $(He)_n$-HCN clusters

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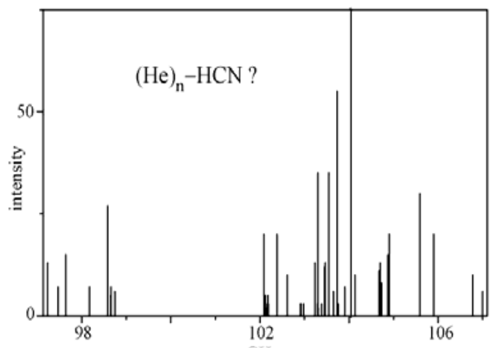
Recent development of the infrared spectroscopy reveals that the superfluidity appears from n=9 for the $(He)_n$-OCS clusters.[1] The superfluidity of the $(He)_n$-HCN clusters may appear from the n value smaller than 9 because the intermolecular interaction energy and the anisotropy of the potential between He and HCN are smaller than those between He and OCS. [2]

In the present research project, we observe the internal rotation bands of the $(He)_n$-HCN clusters by millimeter-wave spectroscopy. The analysis of the internal rotation fine structures observed by millimeter-wave spectroscopy will give us the precise information of the enegy levels and intermolecular interaction potential.

Fig. 1. Observed spectrum.



We have observed the internal rotation and intermolecular stretching bands of He-HCN and determined the intermolecular potential energy surface.[2] Millimeter-wave absorption spectroscopy combined with a pulsed supersonic jet expansion technique has been applied to the observation. Most lines observed are Q-branches for the He internal rotation, which means that the 99.5 % of the He-HCN excited by a millimeter-wave radiation does not change the angular momentum of the He internal rotation and change the angular momentum of the HCN internal rotation or the vibrational energy of the intermolecular stretching vibration. When we have applied high stagnation pressure (～40 atm) to the supersonic jet nozzle, we have observed many weak lines around 100 GHz, which may be the lines of $(He)_n$-HCN. Figure 1 shows the observed spectrum. Some of these lines have nuclear quadrupole hyperfine structures.

We are now developing the low temperature supersonic jet nozzle for the efficient production of the He clusters and the millimeter-wave resonator to improve the sensitivity of the observation of the internal rotation transitions. We are also developing the theoretical prediction method for the internal rotation transitions of He_2-HCN. The method of the analysis and the intermolecular potential energy surface will be discussed.

[1] J. Tang *et al.*, Science **297**, 2030 (2002)
[2] K. Harada *et al.*, J. Chem. Phys. **117**, 7041 (2002)

A-15-1-4 Crystal growth of solid ^{4}He in the quantum limit

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Very fast growth of the c-facet of a 4He crystal was induced by acoustic waves. The growth velocity was larger at lowe temperatures and saturated below about 400 mK. The growt velocity was proportional to the acoustic wave power, whic cannot be explained by the spiral growth mechanism for th known value of the step mobility.

We developed a step multiplication model[1] by the high powe acoustic waves, based on the recent theory by Parshin an Tsymbalenko[2], and had a reasonable agreement with th observed temperature and power dependence of the growt velocity.

In the talk we will present the experimental results an theoretical analysis together with a future experiment planne for the further understanding of the physics.

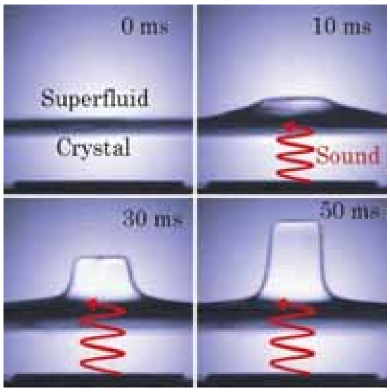

Fig.1 Growth of c-facet of 4He by acoustic waves.

[1] H. Abe *et al*., J. Phys. Soc. Jpn. **75** (2006) 0236011.
[2] A. Ya. Parshin and V. L. Tsymbalenko, JETP Lett. **77** (2003) 321.

A-15-1-5 Field Induced First Order Phase Transition near Absolute Zero Between Nuclear Antiferromagnetic Phases of Solid ^{3}He

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We studied time and spatial evolution of the stable phase during the first order phase transition between U2D2 and CNAF phase, induced by changing the external magnetic field from B_{C1} to $B_{C1}+\Delta B$. The time evolution was classified into two stages. During the first stage, a volume fraction of the metastable phase decreased exponentially in time with a rate γ_1. However in the middle of the process, slower non-exponential second stage took over. This exponential dependence in time suggested that the nucleation process controls the phase transition during the first stage. The termination of the first stage was understood as follows. A nucleated seed grew quickly but eventually stopped growing at a limited size because of the disappearance of the chemical potential difference between two phases due to the heating (cooling) caused by the latent heat release. Each nucleated seeds grew independently in separated location. This process continued until the heated (cooled) region occupied the entire crystal. The model calculation based on this model gave reasonable agreement with our experiment. We also examined the distribution of the seeds during the first stage by ULT-MRI. It was found that the nucleated seeds were located evenly throughout the crystal. The measured nucleation rate suggested that this nucleation should be understood as heterogeneous nucleation. Thus this heterogeneity, which worked as nucleation site, was distributed through out a crystal. The nucleation rate depended more or less similarly to the chemical potential difference, which should be proportional to ΔB. This might be contradictory to the idea of heterogeneous nucleation, since a kind of heterogeneity, which favors one phase, would most probably be unfavorable to the other phase. A possible heterogeneity, which resolves this difficulty, will be proposed.

A-15-2-1 **Two-dimensional ^{3}He film on graphite in high magnetic field**

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A low-density ^{3}He film adsorbed on graphite surface is one of the most ideal two-dimensional (2D) quantum systems. With increasing the density, the second layer varies from an anomalous liquid with three heat capacity peaks[1] to a Mott localized solid. In the so called 4/7 commensurate phase, the ground state is believed to be a gapless spin liquid [2],[3]. The magnetization curve recently obtained from a double gradient Faraday method and NMR are presented , suggesting the existence of plateau and no saturation even at 1 mK and 10 T. While in the liquid phase just before solidification, the heat capacity peak around 30 mK is found to be independent of magnetic fields up to 8T, being attributable to motion of vacancies in the 4/7 phase.

[1] Y.Matsumoto et al., J. Low Temp. Phys. **138**, 271 (2005).
[2] K. Ishida *et al*., Phys. Rev. Lett. **79**, 3451 (1997)
[2] R.Masutomi *et al*., Phys. Rev. Lett. **92**, 025301 (2004).

A-15-2-2
Octupolar order in the multiple spin exchange model on a triangular lattice

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[3]*H. H. Wills Physics Laboratory, University of Bristol, BS8-1TL, UK.*

Motivated by gapless spin liquid observed in solid ^{3}He films, we studied the two-dimensional ring-exchange model with competing FM two-spin interaction (J) and AF ring-exchange interaction (K). We presented a new scenario for the breakdown of FM order. Dynamical effects lead to the formation of magnon bound states, which undergo Bose-Einstein condensation, giving rise to magnetic multipolar order. This scenario was explored in some detail for the ring exchange model on a square lattice [1] and a triangular lattice [2].

For the triangular lattice, we showed how a gapless spin liquid with hidden octupolar order arises in applied magnetic field. In particular, we presented numerical evidence confirming the existence of this new phase, lying between the saturated FM and AF phases. Evidence is also presented for nematic correlations bordering on ferromagnetism in the absence of magnetic field.

[1] N. Shannon, T. Momoi, and P. Sindzingre, Phys. Rev. Lett. **96**, 027213 (2006).
[2] T. Momoi, P. Sindzingre, and N. Shannon, preprint.

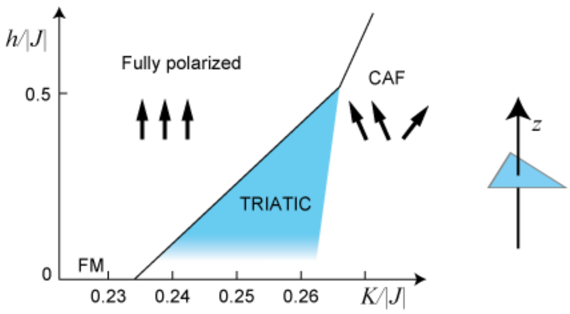

Figure: (Left) Phase diagram for the J-K model on a triangular lattice in applied magnetic field ($J < 0$, $K > 0$). A "triatic" phase with magnetic octupolar order appears between fully polarized and canted AF (CAF) phases. (Right) Spin structure of this triatic order, which is invariant under spin rotations of $2\pi/3$ about the z-axis.

A-15-2-3 Magnetic Properties of Spin Nematic State

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Spin-liquid like properties have recently been observed in several systems with triangular lattice structure; ^{3}He thin film, κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$, and NiGa$_2$S$_4$. These systems do not show indication of magnetic long-range order at temperatures much lower than their Weiss temperature. The last material NiGa$_2$S$_4$ shows power-law behavior in specific heat $C(T) \sim T^2$ and finite magnetic susceptibility [1], indicating the presence of gapless excitations with linear dispersion. Recently we have proposed a scenario based on antiferro spin nematic order and explained most of these properties consistently [2]. One of the most striking features in this system is insensitivity of specific heat to applied magnetic field at low very low temperatures, since a finite induced moment means the change of the ground state. In this report, we will discuss the effects of magnetic field in spin nematic ordered state and dynamic response including NMR relaxation rate.

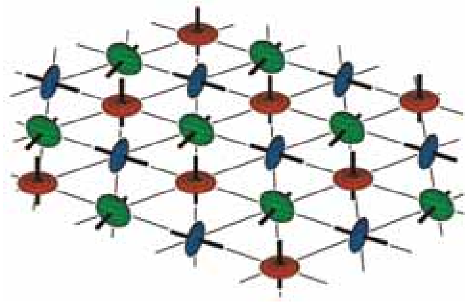

FIG.: 3-sublattice nematic order on a triangular lattice.

[1] S. Nakatsuji *et al*., Science. **309** (2005) 1697.
[2] H. Tsunetsugu and M. Arikawa, J. Phys. Soc. Jpn. **75** (2006) 083701.

A-15-3-1 Magnetic phase diagram of spin-1/2 two-leg ladder with four-spin ring exchanges

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The spin-1/2 two-leg ladder with four-spin ring exchanges under a magnetic field is studied. In the absence of the field, it has been shown that the system with large enough ring exchanges exhibits exotic ground-state phases, including the scalar-chirality phase and the rung-singlet phase with a dominant vector-chirality correlation [1,2]. We discuss two exact duality transformation in the system; one is the spin-chirality duality introduced in [1] and the other is a new one derived in this work. Applying these transformations, we derive two duality relations between various parameters as well as parameter points of the model Hamiltonian. Further, using the duality relations and numerical exact diagonalization technique, we determine the magnetic phase diagram, which includes Tomonaga-Luittinger liquid phases with various dominant correlation functions.

[1] T. Hikihara, T. Momoi, and X. Hu, Phys. Rev. Lett. 90, 087204 (2003).
[2] A. Laeuchli, G. Schmid, and M. Troyer, Phys. Rev. B 67, 100409(R) (2003).

A-15-3-2

Novel ordering of frustrated 2D triangular and 3D pyrochlore systems

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We wish to talk about our research plan on frustrated systems in this project. It includes;

1) Nature of the Z_2-vortex order in 2D triangular Heisenberg antiferromagnet and its possible relation to nuclear magnetism of ^3He and to spin-liquid state of $NiGa_2S_4$.
2) Nature of the ordering of the Ising pyrochlore model with the long-range RKKY interaction and its possible implication to pyrochlore magnet $Pr_2Ir_2O_7$.
3) Nature of the superfluidity transition of 2D helium-three film.

In the workshop, we mainly wish to refer to the topics 1) and 2).
After briefly explaining our motivation of the study, we outline the strategy of the calculation, and present some preliminary results of our numerical simulations.

A-15-3-3

Ring Exchange Induced Charge Stripes in 2D t-J Model

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We investigate the square-lattice t-J model with four-spin ring exchange interactions, using the numerical exact diagonalization of finite-size clusters. In our previous study[1], a possible mechanism of the charge stripes based on the ring exchange interaction was proposed. Further analyses on the multi-hole correlation functions indicates that the diagonal stripe is also possible, as well as the vertical stripes for some parameters. A preliminary phase diagram is presented.

In addition some other ring exchange induced phenomena in the spin ladder[2] will be also proposed.

[1] T. Sakai: Phys. Rev. B 63 (2001) 140509; J. Phys. A: Math. Gen. 36 (2003) 9303.
[2] T. Sakai and K. Okamoto: J. Phys. Chem. Solid 66 (2005) 1450.

A-15-3-4

Quantum and Topological Orders of Quantum Liquids: use of Berry Connection and Entanglement Entropy with Bulk-Edge Correspondence

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Quantum liquids are characterized by the absence of local order parameter to describe the phase with its symmetry breaking. Any observables with classical correspondences are invariant under the base change of wavefunctions (unitary transformation). In the quantum world, however, another type of quantities is also allowed as an observable such as interference amplitude of two different wavefunctions. By an overlap of quantum states with infinitesimal difference, we define the Berry connection, which is not invariant by the base change and undergoes a gauge transformation. Using this Berry connection, we define several quantized quantities as quantum local or global order parameters, especially with finite excitation gap[1].

By these quantum order parameters, we define a topological order and quantum order for the quantum liquids. Quantum Hall states, RVB states, spin gapped phases of correlated electrons such as Haldane phases of spin chains and dimer spins are typical examples [1,2]. Studies on these nontrivial topological and quantum ordered states suggest an importance of hidden non-locality of the quantum state. It implies bulk-edge correspondence, which insists inherent relations between physics of the bulk and the boundaries.

In view of this bulk-edge correspondence, it is natural to use entanglement of a quantum wavefunction for a global characterization.of quantum liquids. Although any classical local order parameters can be short-ranged in the gapped quantum liquid, the entanglement of the quantum state manifests non trivial edge states of the quantum liquid, which is characteristic to the quantum and topological ordered states. We use the entanglement entropy to characterize this bulk-edge correspondence. This is defined by an entropy of the partial density matrix that is obtained by spatially reducing the total density matrix of the pure state[3].

[1] Y. Hatsugai, J.Phys.Soc.Jap. 74 (2005) 1374, ibid 73 (2003) 2604, cond-mat/0603230 to appear in J. Phys. Soc. Jpn., cond-mat/0607024 to appear in J. Phys. C condensed matt.
[2] I. Maruyama and Y. Hatsugai, unpublished.
[3] T. Hirano and Y. Hatsugai, unpublished.

A-16-1-1

Symmetry Breaking in Dilute Bose-Einstein Condensates

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Gaseous Bose-Einstein condensates (BECs) offer a unique testing ground for studying symmetry breaking because trapped BEC systems are in a mesoscopic regime and situations exist under which symmetry breaking may or may not occur. Investigation of this problem elucidates the dynamics of symmetry breaking in a rich variety of systems. We substantiate these ideas in two examples, namely, spontaneous magnetization and chiral symmetry breaking [1] in spinor BECs, and texture formation in dipolar BECs [2]. Our study has direct relevance to the Kibble-Zurek mechanism in the context of nucleation of spin vortices.

[1] H. Saito, Y. Kawaguchi, and M. Ueda, Phys. Rev. Lett. **96**, 065302 (2006).
[2] Y. Kawaguchi, H. Saito, and M. Ueda, Phys. Rev. Lett. 080405 **96** (2006); ibid. **97**, 130404 (2006).

A-16-1-2

Dynamics of atomic Bose-Einstein condensates with internal degrees of freedom

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We have experimentally studied the dynamics of optically trapped gaseous Bose-Einstein condensates (BEC). Thanks to its rich variety of internal degrees of freedom, many interesting dynamics can be observed. First, we studied the spin-mixing dynamics of ^{87}Rb spin-2 (F=2) BEC for deferent initial states. When all the atoms were initially in $m_F=0$ state, spin relaxations to $m_F=\pm1$ and $m_F=\pm2$ states were observed and the population oscillation between these states occurred at certain magnetic field strengths. For $m_F=\pm2$ initial states at weak magnetic field, atoms remained in the initial state. These results strongly suggest that the ground state of F=2 ^{87}Rb BEC is antiferromagnetic. Second, we optically confined binary (F=1 & F=2) BEC, and observed spatial separation and center of mass movement of F=1 and F=2 atoms. This means that F=1 and F=2 BEC are immiscible. The most interesting result may be the appearance of domain structure during “tunneling process”. Thirdly, we have created charge-4 vortex via the magnetic field reversal method. We could observe vortex up to 10 msec in a magnetic trap and up to 20 msec in an optical trap. In the optical trap experiment, the appearance of two vortex cores was observed.

A-16-1-3

Numerical Observation of Kolmogorov Spectrum in Rotating BEC
I. Time Evolution of Energy Spectrum and Vortex Dynamics

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M. Kobayashi[3] and M. Tsubota[3]

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Since the observation of Bose Einstein condensate (BEC) in atomic gases, a renewed interest has been aroused on the quantized vortex structure and its dynamics in the atomic BEC. On the other hand, the quest of vortex dynamics in He^4 or He^3 is now directed toward an old but universal and fundamental problem. The issue is called "Quantum Turbulence", in which Kolmogorov spectrum has been experimentally and numerically studied[1]. In this presentation, we suggest that the Kolmogorov spectrum is also directly observable in rotating BEC of atomic gas. In order to demonstrate the idea, we perform direct simulations for the Gross-Pitaevskii equation with a phenomenological damping which is determined so as to reproduce the experimental results and monitor E(k) from a moment starting the rotation to a steady vortex lattice. The simulation results reveal that E(k) shows a power law obeying $k^{-5/3}$ in an order of k before forming the steady lattice. Figure 1 displays three typical snapshots of temporarily variable energy spectrum E(k, t), in which a transient one (strong dotted line) shows a Kolmogorov spectrum in contrast to those in other times, i.e., the initial(solid line) and the last(weak dotted line) state. This result indicates that the rotating atomic BEC is an alternative excellent stage for catching "Quantum Turbulence".

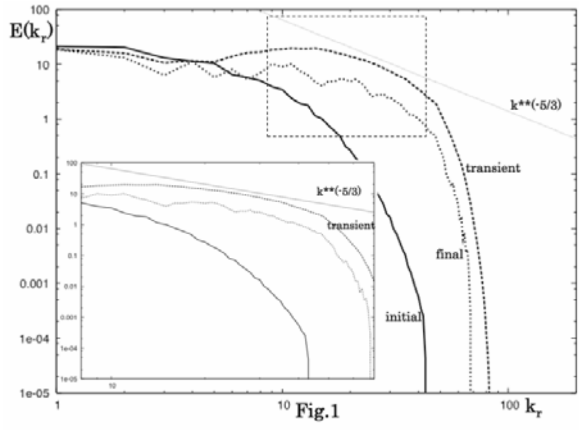

Fig.1

[1] M. Kobayashi and M. Tsubota, Phys. Rev. Lett. 94, 065302(2005).

A-16-1-4

Correlated Fermions in Optical Lattice with Harmonic Confinement

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[3]*NTT Basic Research Laboratories, Atsugi, Kanagawa 243-0198*

We present our recent results on correlated lattice fermions with harmonic confinement, which may be relevant to a cold Fermi gas trapped in an optical lattice. We study several topics: (1) Mott physics in a 1D optical *super*lattice system, (2) time evolution of 1D correlated fermions, (3) stochastic variational Monte Carlo treatment of 2D fermion systems.

Here we focus on the first topic (1D *super*lattice).[1)] In Fig.1, several local quantities calculated by the density matrix renormalization group method are shown for a 1D Hubbard type superlattice system with 2-site periodicity. There are three distinct insulating domains of Mott type, band insulating-type and bond-CDW type. A remarkable point we find is that there is the unusual enhancement of spin correlations (not shown here) between two spatially-separated Mott domains, which is inherent in our optical superlattice system.

We also discuss the topics of (2) and (3) at the workshop.

1) T. Yamashita, N. Kawakami, M. Yamashita, PRA to appear.

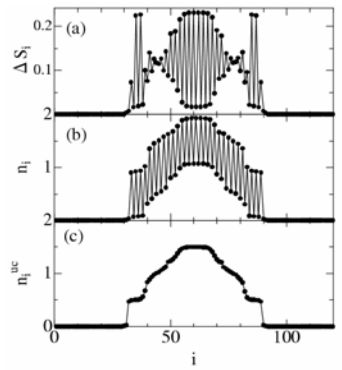

FIG.1: Plots of (a) the variance of local spin fluctuations ΔS_i, (b) the density profile n_i, (c) the density profile n_i^{uc} averaged in the unit cell.

A-16-1-5

Quantum Simulation Using Quantum Degenerate Ytterbium Atoms in Optical Lattices

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[2]*Department of Electronics, Graduate School of Engineering, Kyoto University, Kyoto 615-8510, Japan.*
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The idea that a quantum system which is difficult to control and is never clean can be efficiently simulated by another quantum system which is easy to control and is super-clean, is sometimes referred to as Quantum simulation based on the Feynman's pioneering statement. From this point of view, we are aiming at realizing the quantum simulator of strongly-correlated systems which remain unsolved and are of particular importance in physics, with ultra-cold fermionic atoms in a three-dimensional optical lattice[1]. By performing the quantum simulation, we especially hope to provide a critical insight into the mechanism of the high-T_c superconductivity in cuprates which eluded the unified rigorous theoretical explanation of the observed behaviors, and also the Nagaoka problem on itinerant ferromagnetism. With this cold atom system, we can finely control many important parameters such as temperature, on-site atom-atom interaction, tunneling rates between adjacent sites and layers, filling factor, and so on as well as engineered defect in perfect lattices.

In particular, we plan to work with ytterbium (Yb) atoms since the Yb atoms are less sensitive to an external fluctuating magnetic field and have ultra-narrow optical transitions which are useful to probe weak interactions. Another important advantage of working with Yb atoms is the existence of a rich variety of isotopes, that is, two fermions and five bosons, which will extend the variety of the simulation. So far, we could determine the scattering lengths of all the isotopes including the inter-species scattering length. We have also succeeded in creating 3 BEC and Fermi-degeneracy for Yb. By loading Yb BEC into one-dimensional optical lattice, we observe an interference pattern and momentum distribution in the first Brillouin zone. We will report the present status of our research and the future plan.

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A-16-2-1

Zero-Point Vacancies Doped into a Two-Dimensional Gapless Spin-Liquid

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We have investigated novel quantum states in monolayer helium-three (^{3}He), a strongly correlated fermion system in two dimensions (2D), adsorbed on a graphite surface by heat-capacity and NMR measurements in an extended temperature range ($0.1 \leq T \leq 500$ mK).

This year, Fukuyama group in Tokyo found an experimental evidence for a new quantum state where the fermi liquid picture (Fig. 1A) breaks down near the Mott localization in 2D ^{3}He (Fig. 1B). Measured heat capacities show an anomalous coexistence of a magnetic round-peak near 1 mK (*LT-anomaly*) and another at several tens mK or higher (*MT-anomaly*) in a density range of $0.8 \leq n \leq 1$. Here, $n \equiv \rho/\rho_{4/7}$ is the relative density, and $\rho_{4/7}$ is the density of a low-density registered solid, the so-called "4/7 phase" (Fig. 1C). By incorporating with heat-capacity data of previous workers at higher temperatures (40 mK $\leq T \leq$ 2 K) which show increases of heat-capacity above 1 K (*HT-anomaly*) and comparing with theoretical calculations of heat capacity for the $U = \infty$ Hubbard model on a triangular lattice by Ogata group, we concluded that the *MT-anomaly* is associated with the 2D band of the long-sought "zero-point vacancies" (ZPV) [1]. Our results provide challenging open questions for modern condensed-matter theories including reexamination of the spin-mass separation in 2D.

Morishita group in Tsukuba studied heat capacities of the 4/7 phase, whose ground state is considered to be a gapless spin-liquid, in the presence of magnetic field. We found an anomalously strong field dependence of heat-capacity even in relatively low magnetic fields less than 0.1 T. The results would imply extremely high frustration in this novel magnetic state on a triangular lattice.

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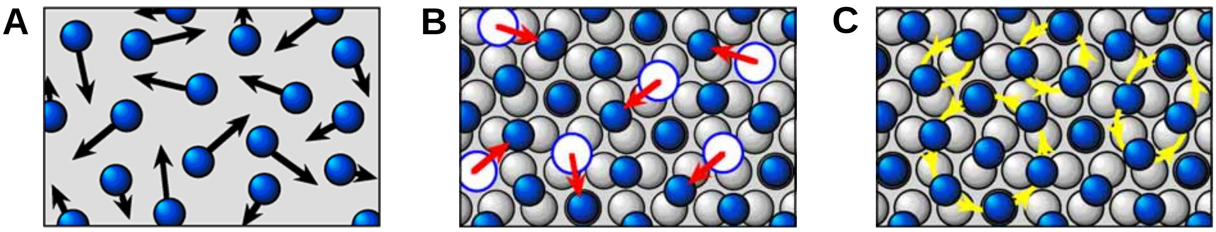

FIG.1: Schematic drawings of **A**) Fermi liquid ($n \leq 0.8$), **B**) ZPV state ($0.8 \leq n \leq 1$) and **C**) 4/7 phase ($n = 1$) in 2D ^{3}He. The bright dots represent ^{3}He and dark ones the underlying ^{4}He.

A-16-2-2 A √7x√7 phase of the second adsorbed ^{3}He layer on a graphite

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We considered an adsorbed second layer of ^{3}He particle on a solidified ^{4}He first layer on a graphite substrate. A density of the first layer was 12.0nm^{-2} which was the maximum density of the stable first layer. The second layer √7x√7 structure of ^{3}He against the first layer was believed to be stable. Then we carried out path integral Monte Carlo calculation for this structure.

First we checked a stability of the ^{3}He first layer. We made inverted configuration, that ^{3}He was located as the first layer and put ^{4}He as the second layer. This configuration was found to be unstable by carrying out the calculation. On the other hand, the normal configuration was found to be stable. Next in order to determine the precise configuration of √7x√7 phase a density profile and Binder parameter of the phase was calculated. Though the convergence of the calculation was poor, we found the melting temperature was estimated as around 1.1K and a distorted structure of √7x√7 became stable.

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A-16-2-3

A Model Calculation of ^{3}He on Two-Dimensional Graphite

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We study temperature dependences of specific heat and susceptibility of ^{3}He absorbed on the two-dimensional graphite at the so-called 4/7-phase (half-filling) of the second layer. When we consider the effects from the first layer, there are two kinds of sites for ^{3}He: One is just on the first-layer atoms (called as B-sites) and the other is above the middle of two adjacent atoms in the first layer (A-sites). Since the onsite potentials on the B-sites will be higher than those on the A-sites, it is natural to expect a larger superexchange interaction between A and A sites than that between A and B sites. A-sites form a two-dimensional Kagome lattice, while B-sites form a triangular lattice which consists of the vacant sites of the Kagome lattice. Thus the ^{3}He system at 4/7-phase can be regarded as a spin system with dominant Kagome interaction, J, and weak coupling, J', between the Kagome and triangular spins. By considering this model, we show that the double-peak structure of specific heat and susceptibility observed experimentally can be understood.

A-16-2-4
Spin Polarization in Strongly Correlated 2D Systems in Semiconductors

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There has been great attention to the fundamental properties of strongly correlated two-dimensional (2D) electron or hole systems that are realized in “super clean” semiconductor interfaces, such as Si metal-insulator-semiconductor field-effect-transistors (Si-MOSFETs) and other semiconductor heterostructures. This is partly due to the observation of the metal-insulator transition (MIT) at low temperatures and zero magnetic fields [1]. On the other hand, it is well-known that the magnetic field parallel to the 2D plane plays essential roles in these systems. Strong positive magnetoresistance [2,3,4] and magnetic-field-induced MIT [5] are discussed in connection with the spin polarization.

Recently, the divergence of the spin susceptibility at or near the MIT has been reported for Si-MOSFETs [1]. The tendency for the spin susceptibility to diverge has also been observed near the solid-liquid transition of 2D ^{3}He systems.

In this work, we have performed systematic measurements of magnetoresistance of a high-quality Si-MOSFET in order to study the electronic and spin states in the insulating regime. The results strongly suggest that no spontaneous full spin polarization occurs even in the far insulating regime.

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A-16-2-5 Novel Quantum Phases in the Bilayer Quantum Hall Regime

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Two-dimensional electron systems (2DESs) are one of the most fascinating *superclean* systems where particularly in the quantum Hall (QH) regime novel quantum phases emerge. In a bilayer QH state consisting of two parallel 2DESs, the layer (pseudospin) degree of freedom, with the spin degree of freedom, leads to a rich variety of quantum phases, because of the competition among various energy scales: Zeeman, tunneling, cyclotron, interlayer Coulomb and intralayer Coulomb energies.

We carry out magnetotranport measurements using a GaAs/AlGaAs double-quantum-well sample with the tunneling energy 11 K. We focus on novel quantum phases in QH states at the total Landau level filling factor $\nu = 1$ and $\nu = 2$ in this workshop. In the $\nu = 1$ bilayer QH state, we find a new pseudospin configuration called soliton lattice (SL) phase manifested by a magnetoresistance peak around the pseudospin commensurate-incommensurate phase transition point. We also find that the SL phase has a highly anisotropic nature. In the bilayer $\nu = 2$ QH state, on the other hand, we demonstrate the emergence of the canted antiferromagnetic phase by elaborate activation energy measurements between the well-known spin-singlet phase and the spin-ferromagnet phase. We make the phase diagram of the bilayer $\nu = 1$ and $\nu = 2$ QH states as a function of the total electron density and in-plane magnetic field.

A-16-3-1 Recent results on Mott criticality in 2D organics

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The experimental study of Mott physics has reached the stage to observe the criticality of Mott transition. So far, the 3D material, V_2O_3 [1], and the 2D material, κ-$(ET)_2Cu[N(CN)_2]Cl$ [2], have served for the experiments. The resultant critical exponents are different between the two systems. Theoretically, there is proposed a concept of "marginal quantum criticality" to solve this interesting controversy [3].

For further experimental investigation on this subject, we have started the transport study for another 2D material, κ-$(ET)_2Cu[N(CN)_2]Br$, which is an isostructural Mott insulator with the Cl version but is situated more closely to the Mott boundary and more anisotropic in the triangular lattice network of the transfer integrals. Even after repeated experiments on many separate crystals, we have not yet obtained the transport criticality data of the same quality as in the Cl version. However, except for the just vicinity of the critical point, the exponents found in the Cl version is reproduced in this material. It is also noted that the critical temperature is appreciably lowered in the Br version. In this meeting, we will present other characteristics of the Mott transition such as profiles of Mott boundary and Fermi liquid-bad metal crossover in P-T diagram, and the control of the Mott transition by regulating the cooling speed of the specimen,.

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A-16-3-2 Novel quantum phenomena in single-layered ruthenates under pressure

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Pressurisation is generally known as a unique technique to tune internal parameters without introducing disorder to a super clean system of single-layered ruthenates. We introduce here a unique pressure-temperature phase diagram of Ca_2RuO_4 and its rich variety of novel quantum phenomena. Firstly, we report that an anisotropic and giant magnetoresistance effect in the vicinity of a pressure induced Mott transition. At ~2GPa, the MR effect reaches ~ − 80% at ~T_C for longitudinal and ~ +80% at low temperatures for the transverse effects. Secondly, we show a pressure-induced phase transition from a Mott insulator with an AF ground state to a Q2D metal with a FM ground state. The small remnant magnetisation ~0.35μ_B (1.5GPa) compared with the saturated moment 2μ_B of localized Ru^{4+} ion implies itinerant FM. With pressurising the FM T_C rises, reaching 25K at ~5GPa, then it decreases gradually. Rapid reduction of T_C at ~ 10GPa suggests the induction of a FM quantum critical-point. We have strong interest in bridging the gap between the triplet superconductivity of Sr_2RuO_4 and the itinerant FM of metallic Ca_2RuO_4.

A-16-3-3

Charge transport at quantum critical point in "clean" NiS_2 pyrite

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NiS_2 pyrite is an antiferromagnetic (AF) Mott insulator. The substitution of S with Se in NiS_2 gives rise to an increased band width and, as a function of Se content, $NiS_{2-x}Se_x$ solid solution shows a transition from the AF insulator to an AF metal and, then, to a paramagnetic (PM) metal. The critical point between the AF metal and the PM metal has been known as a textbook example of antiferromagnetic quantum critical behavior. A non-Fermi liquid behavior of resistivity, $T^{1.5}$ dependence, shows up but only at the critical point and T^2-dependence of resistivity, indicative of a Fermi liquid, rapidly recovers on going away from the critical points.

Application of pressure should give rise to analogous increase of band width without introducing disorder. We have recently succeeded in realizing an antiferromagnetic critical point by applying pressure of ~7.5 GPa on pure (disorder free) NiS_2. The residual resistivity ρ_0 near the critical point was extremely low, 0.2-0.3 μ Ωcm, indicating that this pressure controlled system is indeed much cleaner than the substitution system. We found that the critical behavior of such "clean" system is markedly different from those of "dirty" solid-solution system. Low temperature resistivity of pressurized NiS_2 was insensitive to the presence of critical point.and showed T^2 dependence even at the critical point. We argue that such a distinct behavior in the clean system is due to the anisotropic quasi-particle scattering by anti-ferromagnetic spin fluctuation, namely the presence of hot and cold spots on the Fermi surface. No superconductivity was observed around the critical point at least down to 200 mK., despite the low residual resistivity.

A-16-3-4

Valence Bond States and Pressure-Induced Superconductivity in Quantum Triangular Antiferromagnets, [Pd(dmit)$_2$] Salts

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In a series of [Pd(dmit)$_2$] anion radical salts, an unpaired electron is localized on each dimeric unit, [Pd(dmit)$_2$]$_2^-$. The spin-1/2 units form a 2D quasi-triangular lattice with spatial anisotropy adjustable by the counter cations. Some of the salts exhibit antiferromagnetic long-range order (AF LRO) due to the spatial anisotropy. Unconventional ground states appear, as the AF LRO is suppressed by frustration, when the anisotropy is small. The $P2_1/m$ phase of the EtMe$_3$P salt, for instance, exhibits a second-order phase at 25 K, accompanied by the lattice translational symmetry [1]. This indicates that the valence bonds formed between the neighboring spin-1/2 units are ordered spatially with the help of lattice. Pressure suppresses the valence bond ordering, and superconductivity turns to appear ,suggesting an exotic pairing mechanism operating in the proximity of the valence bond state.

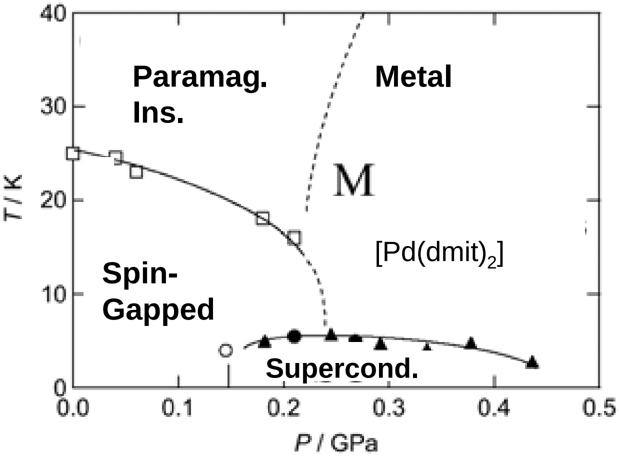

FIG.1: P-T phase diagram of the EtMe$_3$P salt ($P2_1/m$).

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A-16-3-5

Topology transition vs. symmetry breaking at quantum end point of 1st-order transition

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In A01 group we focus on novel quantum phenomena around quantum critical points. In one direction of research, we seek for unexplored quantum liquid phases. ^{3}He on graphite and κ-ET compound exhibit gapless spin-liquid behavior while $NiGa_2S_4$ implies a rather different type of quantum-spin ground states. We have shown theoretically that Hubbard model at half filling on a frustrated square lattice contains unconventional gapless spin-liquid phase surrounded by paramagnetic metals and several different antiferromagnetic insulators. Here, based on the cellular dynamical mean field theory, we propose the existence of another novel ***spin-charge liquid*** in insulating phase at ***quarter filling***, where the lattice structure causes quantum melting of charge-spin orders by geometrical frustration effects.

We also study nature of quantum phase transitions themselves. Continuous phase transitions at finite temperatures are well described by the concept of spontaneous symmetry breaking formulated in Ginzburg, Landau and Wilson scheme. However, quantum systems often show different types of continuous phase transitions characterized by the topology change. We propose a new category of quantum critical points which emerges from the involvement of both the symmetry breaking and the topology change, where an unconventional universality is theoretically and experimentally established. This new concept applies to Mott transition as well as to Lifshitz transition. Such a ***marginal critical point*** appears as an endpoint of first-order transition. In more general, zero-temperature critical points of the first-order transition are also observed in the conventional magnetic transitions as well as in valence transitions. These all in all indicate novel classes of quantum criticality bridging seemingly unrelated and puzzling phenomena found in transition metal, organic and rare-earth compounds as well as in the ^{3}He system and comparisons between the theory and available experiments are satisfactory.