Group Activities

Research Group for Condensed Matter Physics of Heavy Elements Systems

Group Leader: Shinsaku Kambe

In heavy element (f-electron) systems, valence fluctuations, the Kondo effect, and the RKKY interaction compete with one another. Because of this, exotic behaviors such as quantum critical points, heavy fermions, non-Fermi liquids, anisotropic superconductivity and multipolar ordering appear when such competition is strong. Recently, it has become clear that these exotic behaviors for $5f$-electron systems are different from those for $4f$-electrons. This is because electrons with different spin and orbital character can coexist in $5f$ actinide systems, in contrast to the case of $4f$-electrons. By means of microscopic spectroscopy: NMR and μSR, our research group tries to clarify these exotic behaviors due to the "many-fold" character of $4f$, $5f$ compounds, including transuranium. $5f$-electron systems are regarded to possess intermediate physical properties between those of $3d$- and $4f$-electrons systems. The final scientific goal of our project is to unify the concept of magnetism and superconductivity for $3d$ through $5f$ systems.

Correlation between the superconducting pairing symmetry and magnetic anisotropy in *f*-electron unconventional superconductors

The superconducting pairing symmetry and the magnetic anisotropy of the normal state are found empirically to be strongly correlated in f-electron unconventional superconductors having crystallographic symmetry lower than cubic [1]. Effectively, there are three categories: 1)In antiferromagnetic systems, unconventional superconductivity appears with singlet (d-wave) pairing or mixed-parity pairing (in non-centrosymmetric compounds) for cases of XY anisotropy. 2) In ferromagnetic systems, unconventional superconductivity with triplet (e.g. p-wave) pairing appears for cases of Ising anisotropy. 3) A few exceptional cases: The origin of the observed correlation is discussed in terms of the orbital f-electron states. Especially, in the case 1), the larger magnetic XY anisotropy would produce the higher-T_c d-wave superconductivity [2].

Microscopic evidence for magnetic transition in AmO_2

The first NMR study of americium dioxide (AmO_2) has been done. More than 30 years ago, a phase transition was suggested to occur in this compound at 8.5 K based on magnetic susceptibility data, while no evidence had been obtained from microscopic measurements. We have prepared a powder sample of $^{243}AmO_2$ containing 90 at. % ^{17}O and have performed ^{17}O-NMR at temperatures ranging from 1.5 to 200 K. After a sudden drop of the ^{17}O NMR signal intensity below 8.5 K, at 1.5 K we have observed an extremely broad spectrum covering a range of ~14 kOe in applied field (Fig. 1). These data provide the first microscopic evidence for a phase transition as a bulk property in this system [3]. In addition, the ^{17}O NMR spectrum has been found to split into two peaks in the paramagnetic state, which has not been reported for actinide dioxides studied up to now. We suggest that the splitting is induced by self-radiation damage from the alpha decay of ^{243}Am.

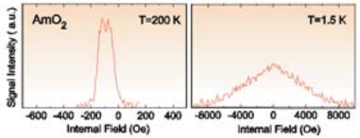

Fig. 1 Temperature dependence of ^{17}O-NMR spectra observed in AmO_2. The shape of the spectrum corresponds to the distribution of hyperfine fields at oxygen nuclear sites. The spectrum in AmO_2 broadens drastically below the ordering temperature of 8.5 K. The line shape in the ordered state is found to be quite different from the rectangular shape observed in the dipole ordered state of UO_2.

f-electron anisotropy locally induced by an interstitial hydrogen analogue μ^+ in $PrPb_3$

There is growing interest in the microscopic knowledge of an interstitial hydrogen in condensed matter and its influence on neighbors. We investigated a microscopic state of the interstitial hydrogen in $PrPb_3$ that is related to lanthanide-based hydrogen absorption metals using a positive muon μ^+ as a hydrogen analogue. We found that the implanted μ^+ is localized at the midpoint between two Pr ions and forms a three spin system Pr-μ^+-Pr, which is evidenced from the time-evolution of μ^+ spin polarization (Fig. 2) [4,5]. The coupling between a ^{141}Pr nuclear spin and a μ^+ spin is anisotropically enhanced by hyperfine-enhanced f-electron magnetic moment. This indicates that the interstitial hydrogen locally induces the strong anisotropy in f-electron magnetism. Based on this study, the effective crystal field at the Pr site in metallic $PrPb_3$ is clarified.

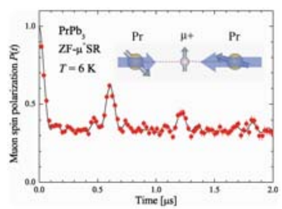

Fig. 2 Time-evolution of μ^+ spin polarization in $PrPb_3$. Characteristic periodic peaks appears due to the formation of Pr-μ^+-Pr system (Inset). The blue arrows represent f-electron magnetic moments induced by the hyperfine interaction with Pr nuclear spins.

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Research Group for Hadron Physics

Group Leader: Kenichi Imai

The research objectives of Research Group for Hadron Physics are 1) experimental study of exotic hadrons and nuclei with strangeness and charm at J-PARC and BNL-RHIC, 2) research and development of new high-rate particle detectors such as a silicon strip detector, a scintillation fiber tracker and a time projection chamber, 3) theoretical study of nuclear matter at high and low densities and the role of strangeness in nuclear matter and neutron stars. Through these topics, we study many-body problems of quarks and hadrons in relation with QCD.

Search for penta-quark Θ^+ with a π beam at J-PARC

The experiment to search for the penta-quark Θ^+ has been performed at J-PARC, through $\pi^- p \rightarrow K^- X(\Theta^+)$ reaction. This was the first experiment in the Hadron hall at J-PARC. The J-PARC hadron beam line (K1.8) provides a π^- beam of 1.9 GeV/c and 10^6 π^-/spill which hits a liquid hydrogen target. Momentum of π^- beam particles is measured by a beam-line spectrometer and that of outgoing K^- mesons is measured with a kaon spectrometer (SKS). The missing-mass resolution for Θ^+ was expected to be about 1.4 MeV/c^2 which is the best resolution among previous penta-quark search experiments. This missing-mass resolution was confirmed by measuring Σ^- hyperons by $\pi^- p \rightarrow K^+ \Sigma^-$ reaction. The data was analyzed in a short period and we found no peak structure due to Θ^+ in the obtained missing-mass spectrum [1]. It concluded that a hint of a possible peak for Θ^+ at 1.53 GeV/c^2 observed by the previous KEK experiment (E522) was due to a statistical fluctuation, since the present data has 10 times more sensitivity to Θ^+ than the previous experiment. The null result provided an upper limit for the production cross section of Θ^+ to be 150 nb at 90% confidence level. It suggests the width of Θ^+ is expected to be about 100 keV or less if it exists, which is quite different from the known hadron resonances.

Research and development (R&D) of high-rate particle detectors for hadron physics experiments at J-PARC

We have been developing three kinds of detectors which have very high rate capabilities. It is quite important and essential to fully utilize the high intensity hadron beams provided by J-PARC. The goal of this R&D is to install tracking detectors capable up to the rate of 10^8 particles/s, which is 100 times higher than the capability of the present detectors at the beam line at J-PARC. The first one is a silicon microstrip detector. We have constructed a silicon strip sensor of 80 μm strip width and sensitive area of 60 $\times$60 mm^2. A test experiment was performed at the Research Center for Electron Photon Science, Tohoku University using a high-intensity electron beam up to more than 10^7 particles/s. We found this detector has a sufficient efficiency (95%) up to 100 MHz particle rate. The second is a time projection chamber (TPC) which is capable of the three-dimensional track reconstruction. We have constructed a small TPC for R&D which has about 25 cm drift length and 10$\times$10 cm^2 sensitive area. In order to have a high rate capability, gas electron multiplier (GEM) sheets with anode pads are employed for the signal amplification and readout. The third one is a scintillating fiber tracker. It has a high rate capability up to 100 MHz particle rates because of an excellent time resolution (less than 1 ns). The construction of a fiber tracker with 1mm ϕ scintillating fibers with micro pixel photon counter (MPPC) readout is now in progress.

Theoretical study of nuclear matter

The equation of state (EOS) of nuclear matter during the liquid-gas (LG) phase transition is one of the most important issues in nuclear physics and astrophysics. In the collapsing stage of supernovae and the crust region of neutron stars, low-density and inhomogeneous nuclear matter is expected. The EOS of mixed phase is often obtained by simply applying the Maxwell construction or more carefully by solving the Gibbs conditions. The Maxwell construction can be used in the case of *congruent* transition: the coexisting two phases have the same chemical component with different densities. However, nuclear matter which consists of proton, neutron and electron, generally becomes *non-congruent* and the particle fractions take different values in coexisting phases. The Gibbs conditions then give EOS different from that of the Maxwell construction.

In the viewpoint of the congruence, we have clarified properties of symmetric and asymmetric nuclear matter. Without considering the geometrical structures, symmetric nuclear matter behaves *congruently* due to the strong symmetry potential. Therefore the Maxwell construction is applicable. Asymmetric nuclear matter, on the other hand, is *non-congruent* and the Maxwell construction does not work.

Subsequently we have explored LG mixed phase with geometrical structures called nuclear "pasta". We have clarified the effects of the surface tension and the Coulomb repulsion on the "pasta" structures. These finite-size effects restrict the appearance of mixed phase with "pasta" structures [2,3].

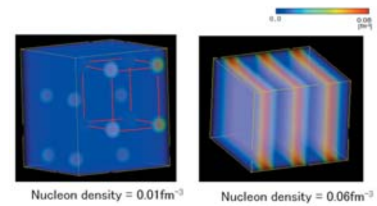

Fig. 1 Examples of "pasta" structures by a fully three-dimensional calculation.

To understand LG mixed phase in more detail, we have performed a fully three-dimensional calculation without assuming geometrical symmetry in the structure. As shown in Fig. 1, we have observed typical "pasta" structures, which was expected in the studies which assume geometrical symmetry. On the other hand we have observed more complex structures with networks of matter or mixture of two kinds of pasta structures. They may emerge as the meta-stable states of matter.

References

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