Research Group for Condensed Matter Physics of Heavy Element Systems

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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 5*f*-electron systems are different from those for 4*f*-electrons. This is because electrons with different spin and orbital character can coexist in 5*f* actinide systems, in contrast to the case of 4*f* 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 both 4*f* and 5*f* compounds, including transuranium.

Emergence of antiferromagnetism out of 'hidden order' state in URu_2Si_2 [1]

The so-called "hidden-order" (HO) phase transition in the heavy-fermion compound URu_2Si_2, at transition temperature T_O=17.5 K, has posed a long-standing mystery. URu_2Si_2 is also a very attractive material displaying intriguing *T-H* phase diagrams. In particular, an anomaly in the Hall resistivity around H^*~22 T has been reported within the HO phase [2]. It is also reported that the critical field of HO phase is about $H_c \sim 35$ T by means of resistivity measurements [3]. High field NMR is a very suitable microscopic technique to investigate these anomalies in URu_2Si_2. The single crystals studied in our international project with NHMFL and LANL teams were enriched with 99.8% of ^{29}Si isotope, a very suitable nucleus (I=1/2) for NMR measurements. It is worth briefly mentioning few striking NMR results: the low-*T* ^{29}Si-NMR shift (K) anomaly around H^* and the critical increase of K towards H_c. Both results must be related to crucial changes in the Fermi surface of URu_2Si_2. Another remarkable result is the complex ^{29}Si-NMR spectrum in the adjacent magnetic phase II to the HO state as displayed in Fig. 1. This spectral shape can be understood by an antiferromagnetic ordering of Ising-type localized spin arrays, as illustrated in the inset of Fig. 1. The ordered moment of ~0.6 μ_B/U in phase II is estimated by considering the hyperfine coupling constant A^c_{hf}=3.4 kOe/μ_B obtained in the PM and HO phases.

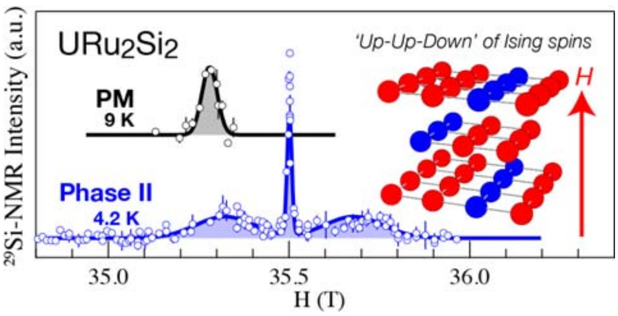

Fig.1 ^{29}Si-NMR spectra in the PM and Phase II states for URu_2Si_2. The inset shows a possible magnetic structure of Phase II, which is an up-up-down' AFM arrangement of Ising-type spins.

Coexistence of quadrupole ordering and superconductivity in $PrRh_2Zn_{20}$ [4]

f-electrons of rare-earth and actinide ions support a variety of multipole degrees of freedom. In a highly symmetric crystalline-electric-field (CEF) potential, the multipole degrees of freedom survive even at low temperatures in some cases and a degenerated CEF ground state with multipoles is realized. Meanwhile, unconventional superconductivity is seen in several *f*-electron systems. In most of them, the origin of the superconductivity is believed to be a magnetic interaction. However, superconductivity also occurs in a few systems with a non-magnetic CEF ground state, and it is being suggested that the multipole fluctuation mediates the electron pairing interaction. Therefore, the interplay between superconductivity and multipoles in *f*-electron systems is important for the investigation of the novel mechanism of electron pairing. Recently, heavy fermion behavior was found in a Pr-based compound $PrRh_2Zn_{20}$ [5]. The CEF ground state of Pr ions in $PrRh_2Zn_{20}$ is suggested to be a non-magnetic Γ_3 doublet from magnetization measurements. In addition, superconductivity was found below T_c=0.06 K. Since the non-magnetic CEF ground state is suggested, quadrupole interactions may play an important role in its superconductivity. Furthermore, recent low-temperature specific heat measurements revealed another phase transition at T_Q=0.06 K (the same temperature with T_c), suggesting quadrupole ordering. Therefore, the coexistence and interplay of superconductivity and quadrupole ordering are strongly implied. We performed μSR measurements in $PrRh_2Zn_{20}$ at J-PARC to elucidate its magnetic and superconducting properties. Temperature-independent μSR spectra were observed below 1 K in zero applied field, as shown in Fig. 2, indicating that the phase transition at T_Q is of a non-magnetic origin, most probably pure quadrupole ordering. In the superconducting phase, no sign of unconventional superconductivity, such as superconductivity with broken time-reversal symmetry, was seen below T_c.

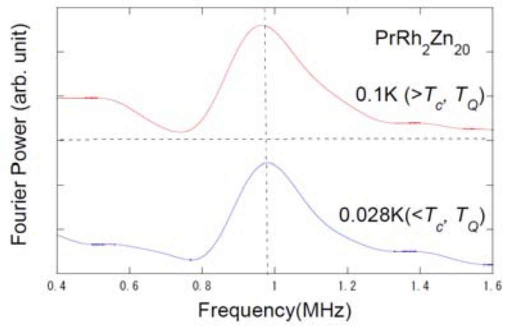

Fig. 2 Fourier power of zero-field μSR spectra in $PrRh_2Zn_{20}$.

References

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