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.

Microscopic studies of nonmagnetic multipolar ordering and multipolar fluctuations in Pr*Tr*$_2$Al$_{20}$ (*Tr*: Ti, V)

The discovery of heavy fermion superconductivity in $PrTi_2Al_{20}$ has stimulated a renewed interest in a novel superconducting mechanism mediated by electric quadrupolar fluctuations [1]. The cubic $PrTr_2Al_{20}$ compounds (*Tr*: Ti, V) have the Γ_3 crystalline-electric-field (CEF) ground state and exhibit multipolar ordering at T_O=2.0 K (Ti) and 0.6 K (V), likely because of the quadrupolar interactions in the Γ_3 subspace [2]. The temperature dependences of specific heat, electric resistivity, and magnetic susceptibility suggest that the quadrupolar Kondo effect sets in at low temperatures. The superconducting transition in $PrTi_2Al_{20}$ occurs at 0.2 K in the multipolar ordering state, implying possible correlations between the superconductivity and the quadrupolar fluctuations.

All these arguments on $PrTr_2Al_{20}$ postulate that the quadrupolar interactions are dominant among allowed multipolar interactions at low temperatures. However, no such evidence has been provided yet. We have thus performed complementary μSR and NMR studies on $PrTr_2Al_{20}$ and elucidated their electronic states from microscopic viewpoints.

μSR measurements were carried out at MUSE, J-PARC, Japan, and PSI, Switzerland. The muon spin relaxation rate of $PrTi_2Al_{20}$ was measured down to 0.1 K in zero field (ZF) and no significant change was observed while passing through T_O=2.0 K (Fig.1). This suggests that the order parameter is an electric multipole, most probably an electric quadrupole that is active in the Γ_3 subspace. We also found that slow spin fluctuations remain even at 0.1K well below T_O, ascribed to ^{141}Pr hyperfine-enhanced nuclear magnetism characteristic of the nonmagnetic CEF ground state [3]. In PrV_2Al_{20}, no evidence of magnetic ordering was detected down to 3 K. The ^{141}Pr hyperfine-enhanced nuclear magnetism was also observed, which is consistent with the Γ_3 CEF ground state. μSR measurements of PrV_2Al_{20} in the multipolar ordered state below T_O=0.6 K is now in progress.

To gain further information on the spin fluctuations of this system, we have performed Al-NMR under magnetic field. Analysis of the spin-lattice relaxation rate $1/T_1$ reveals that magnetic fluctuations are dominated by the strong *c*-*f* exchange coupling at high temperatures and thus is nicely consistent with the Kondo picture that features ln*T* dependence of resistivity (Fig. 2). Furthermore, $1/T_1$ was found to exhibit strong field dependence in $PrTi_2Al_{20}$ at low temperatures, where $1/T_1$ increases significantly as the field is increased. The anomaly is not due to the fluctuations of ^{141}Pr nuclear spin, since the effect must be suppressed under magnetic field, as confirmed by μSR [3]. We have thus suggested that the anomaly might arise from fluctuations of field-induced moments associated with instability of the ferro-quadrupole phase transition under magnetic field [4]. The present μSR and NMR reveal that this unique system involves full of interesting relaxation effects that have never yet been observed.

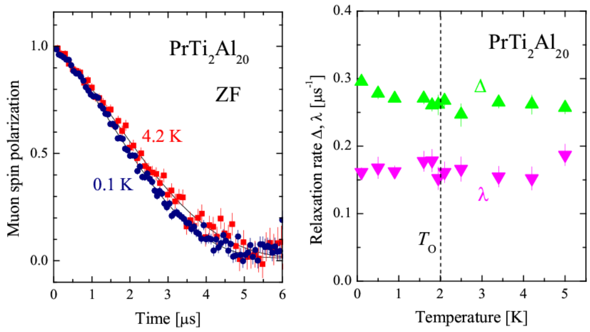

Fig.1 The ZF-μSR spectra in $PrTi_2Al_{20}$ at 0.1 and 4.2 K (left) and the muon spin relaxation rates Δ and λ as functions of temperature (right). The Δ and λ were obtained by fitting the ZF-μSR spectra to $G_{KT}(t;\Delta)*\exp(-\lambda t)$, where $G_{KT}(t;\Delta)$ is the Kubo-Toyabe function.

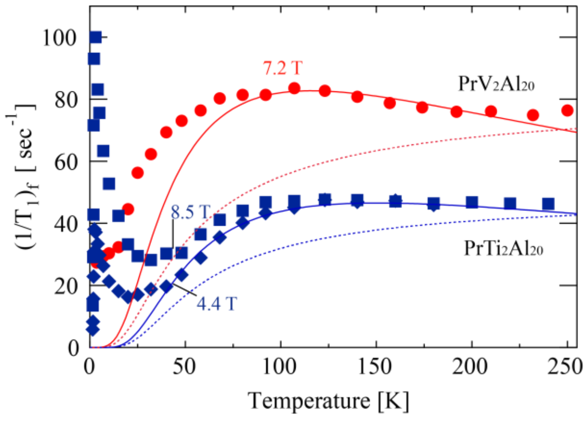

Fig.2 The temperature dependence of $(1/T_1)_f$ (contribution from Pr 4*f* electrons). The solid and dotted lines were calculated for magnetic fluctuations dominated by the *c*-*f* and the *f*-*f* exchange type interactions, respectively.

References

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