# 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 4f and 5*f* compounds, including transuranium.

**Non-collinear antiferromagnetic ordering and new type of multipolar frustration in $TbCoGa_5$**

$HoCoGa_5$ type structure (115) compounds are particularly interesting since many fascinating phenomena are observed *i.e.* unconventional superconductivity near a magnetic quantum critical point (as shown in research highlight for $CeCoIn_5$), and phase transition related with multipolar ordering. In this context, it is quite important to understand magnetic interactions between *f*-electrons in the 115 systems. A 115 type compound $TbCoGa_5$ shows successive two antiferromagnetic transitions. From neutron diffraction measurements, there are two ordered states AF-I (high $T$ phase below $T_{N1}$=36 K) and AF-II (low $T$ phase below $T_{N2}$=5.4 K). Tb moments order in a stripe fashion along the *c*-axis in the AF-I phase, and an ordering in the ab-plane is finally established in the AF-II phase. Unfortunately, the neutron measurements could not distinguish collinear from non-collinear structure of the AF-II phase. If non-collinear structure is the case, it is particularly interesting since such behaviour suggests a magnetic frustration in the ab-plane.

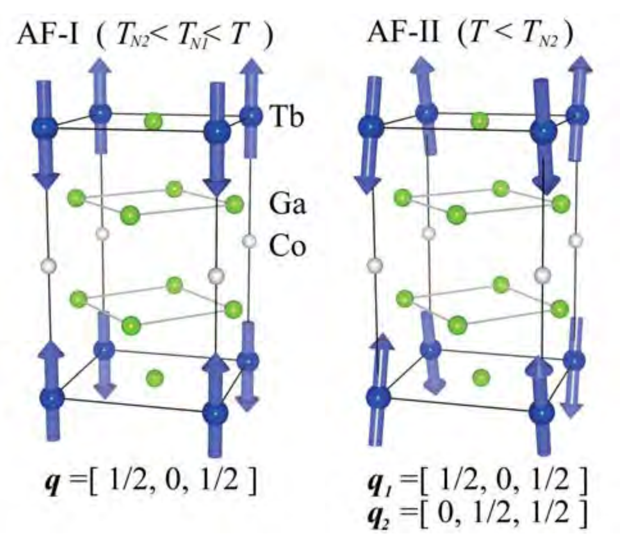


Fig. 1 Antiferromagneically ordered structures in $TbCoGa_5$. Collinear AF I at high temperatures $T_{N2}<T<T_{N1}$ (left) and non-Collinear AF II at low temperatures $T<T_{N2}$ (right). $\boldsymbol{q}$ is ordering wave vector.

Based on the Ga-NMR in $TbCoGa_5$, the AF-II has been actually identified as non-collinear phase for the first time (Fig. 1) [1]. Generally, non-collinear structure can appear to reduce frustration, whereas there is no geometrical frustration in $TbCoGa_5$, indicating that there may be a new mechanism of frustration. Now a possible mechanism *i.e.* frustration between dipolar and quadrupolar interactions is investigated.

**Coexistence of superconductivity and multipolar ordering in $PrIr_2Zn_{20}$**

$PrIr_2Zn_{20}$ belongs to caged compounds $RT_2X_{20}$ having the cubic $CeCr_2Al_{20}$-type structure where R atoms are encapsulated in cages formed by 16 zinc atoms. In a $RT_2X_{20}$ system, a multipole phase transition is expected to occur owing to the highly degenerate ground state. Among these systems, $PrIr_2Zn_{20}$ is particularly interesting since ac-magnetic susceptibility measurements revealed superconductivity below 0.05 K. Furthermore, recent low-temperature specific heat measurements reveal another phase transition below 0.11 K, although the origin of transition has not been identified.

To elucidate magnetic and superconducting properties, we performed muon spin rotation and relaxation measurements (μSR) in $PrIr_2Zn_{20}$ at very low temperatures [2]. As shown in Fig. 2, temperature independent μSR spectra were observed below 1 K, indicating that a phase transition at 0.11 K 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 $T_c$=0.05 K. The present measurement indicates that a coexistence of superconductivity and quadrupolar ordering may be realized in $PrIr_2Zn_{20}$. Now relation between the superconductivity and quadrupolar fluctuations is investigated.

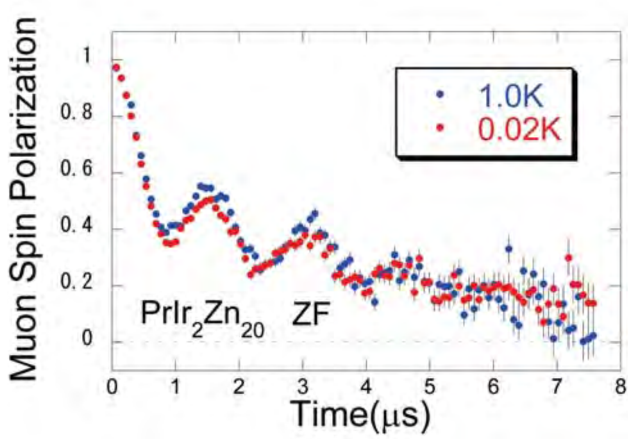


Fig. 2 Zero field (ZF) μSR spectra in $PrIr_2Zn_{20}$ at 1.0 K and 0.02 K.

**References**
[1] Y. Tokunaga *et al*., Phys. Rev. B **84**, 214403 (2011).
[2] W. Higemoto *et al*., to appear in Phys. Rev. B.