Magnetic Excitation in the Antiferro-Type Multipolar Ordering Phase of $PrFe_4P_{12}$

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$PrFe_4P_{12}$ has recently attracted much attentions because of the heavy electron behavior that is novel for Pr-based compounds (H. Sugawara *et al.*: Phys. Rev. B **66** (2002) 134411, H. Sato *et al.*: Phys. Rev. B **62** (2000) 15125). It undergoes a nonmagnetic phase transition at $T_A = 6.5$ K (Y. Aoki *et al.*: Phys. Rev. B **65** (2002) 064446, L. Keller *et al.*: J. Alloys and Compounds **323-324** (2001) 516). X-ray superlattice reflections characterized by the wave vector $\mathbf{q} = (1\,0\,0)$ were observed below T_A (K. Iwasa *et al.*: Physica B **312-313** (2002) 834). Our neutron diffraction study revealed antiferromagnetic reflections induced by magnetic fields below T_A. These phenomena indicate antiferro-type ordering of the $4f$ electrons of Pr ions (L. Hao *et al.*: Acta Physica Polonica B **34** (2003) 1113). Recently, this antiferro-type ordered phase has been interpreted as the Γ_1-type or scalar-type order of higher-rank multipole that does not break the local symmetry (A. Kiss and Y. Kuramoto: J. Phys. Soc. Jpn. 75 (2006) 103704). In the heavy electron phase, magnetic excitation spectra from the polycrystalline sample are heavily overdamped and quasielastic (K. Iwasa *et al.*: Acta Physica Polonica B **34** (2003) 1117). This fact indicates that the $4f^2$ electrons of Pr^{3+} ion hybridize strongly with carriers. Since elementary excitation in the multipolar ordering phase is an interesting subject, we performed inelastic neutron scattering measurements for single crystal samples.

Inelastic neutron scattering experiments were carried out on the cold- and thermal-neutron spectrometers HER (C1-1) and TOPAN (6G), respectively.

Figure 1 shows energy spectra at $\mathbf{Q} = (0\ 1.9\ 0)$ obtained in the HER experiment. At zero magnetic field at 1.6 K, two sharp peaks appear at 1.5 and 3.2 meV, in contrast to the quasielastic response above T_A, although it is not shown here. We have already confirmed that these excitations are less dispersive, so that they are originated from the excitations in low-lying crystal-field levels. These peaks are considered to be elementary excitations in the higher multipolar ordering phase. When the magnetic field was applied to 2.75 T corresponding to the intermediate region of the ordered phase, the 1.4 meV peak seems to split in two or three peaks. This phenomenon can be naively understood as a lifting of the crystal-field-level degeneracy. As discussed recently, the Γ_1-type or scalar-type order conserves the local symmetry and the crystal-field level splitting thorough the transition temperature, although the two Pr ions in the bcc unit cell become inequivalent. This scenario is consistent with the observed splitting of the excitation peak.

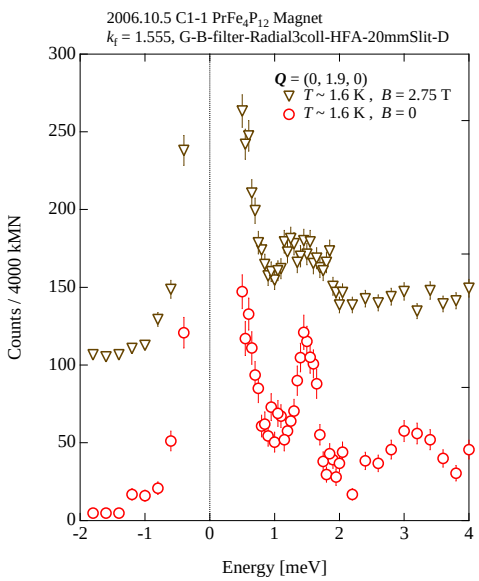

Fig. 1. Inelastic magnetic neutron scattering profiles at $\mathbf{Q} = (0\ 1.9\ 0)$ in the ordered phase of $PrFe_4P_{12}$.