Magnetic Excitation of Ferromagnetic System $NdFe_4P_{12}$ Exhibiting Heavy Electron Behavior

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In the study of strongly correlated electron phenomena of rare-earth filled skutterudite compounds, heavy electron state in the system having two or more $4f$ electrons per rare-earth ion has been a topic. $PrFe_4P_{12}$ with $4f^2$ configuration of Pr^{3+} is a typical system, which shows the Sommerfeld coefficient for electronic specific heat γ = 1.4 J/mol/K^2 and the clear -log$T$ behavior of electrical resistivity (Y. Aoki *et al.*: Phys. Rev. B **65** (2002) 064446, H. Sugawara *et al.*: Phys. Rev. B **65** (2002) 134411). Our inelastic neutron scattering experiment revealed the quasielastic magnetic response indicating the strongly hybridized state (K. Iwasa *et al.*: Acta Physica Polonica B **34** (2003) 1117). A similar $-\log T$ behavior is also found in $NdFe_4P_{12}$ with $4f^3$ configuration of Nd^{3+} (H. Sato *et al.*: Phys. Rev. B **62** (2000) 15125). However, it undergoes a ferromagnetic phase transition at T_C = 1.9 K and the magnitude of ordered magnetic moment was evaluated as $1.6\mu_{B/Nd}$ (L. Keller *et al.*: J. Alloys and Compounds **323-324** (2001) 516), which is much larger than the typical heavy electron materials and seems not to be consistent with the singlet formation due to Kondo effect. Thus, the heavy electron behavior in electrical resistivity of $NdFe_4P_{12}$ together with well localized $4f$ electrons is a mysterious property. In order to investigate the $4f$ electron state of this material, we performed inelastic neutron scattering experiments. The triple-axis spectrometers TOPAN (6G) and HER (C1-1) were used to measure energy spectra from a single-crystalline sample.

Figure 1 shows energy spectra at **Q** = (0.85 0.85 0) of $NdFe_4P_{12}$ at 0.7 and 3 K above and below T_C, respectively. We observed a peak at 1 meV at 0.7 K and it disappears at 3 K above T_C. This peak can be assigned to a collective excitation in the ferromagnetic ordered state, and no distinct dispersion relation is detected near the ferromagnetic zone center **Q** = (1 1 0). It is indicative that the magnetic excitation has energy gap of 1 meV, which may come from the anisotropy of crystal field. The magnetic excitation is consistent with the ferromagnetic ordering, so that the anomalous behavior of $NdFe_4P_{12}$ can not simply be attributed to the magnetic Kondo effect.

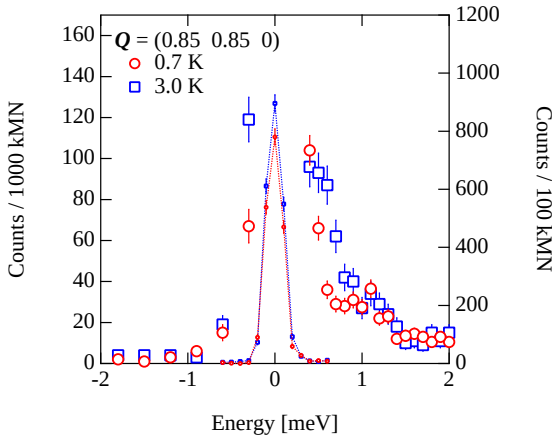

Fig. 1. Energy spectra at **Q** = (0.85 0.85 0) of $NdFe_4P_{12}$ at 0.7 and 3 K.