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New High-Field Ordered State in $PrFe_4P_{12}$

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$PrFe_4P_{12}$ has attracted considerable attention because of the anomalous ordered state (phase A), apparent Kondo effect and heavy fermion behavior. Recently, we showed the presence of a new ordered state (phase B) in high fields applied along the [111] direction [1]. In this talk, we discuss a possible origin of the B phase within the framework of the Γ_1–Γ_4 model.

Aoki *et al.* proposed two CF schemes for $PrFe_4P_{12}$ based on the analysis of the anisotropy in the magnetization and the electronic entropy associated with the A-phase transition, i.e., Γ_3(0K)–Γ_4(18K) (scheme A) and Γ_1(0K)–Γ_4(13K) (scheme B) [2]. To investigate the field dependence of the two CF schemes, we carried out numerical calculations using the Hamiltonian $H_0 = H_{\rm CF} - g_{\rm J}\mu_{\rm B}\mathbf{J}\cdot\mathbf{H}$. Figures 1(a) and 1(b) shows the energies of the CF levels as a function of magnetic field applied along the [111] direction in schemes A and B, respectively. In scheme A, no level crossing of the two lowest levels arises, whereas a crossing occurs around 11 T in scheme B. By analogy with $PrOs_4Sb_{12}$, one may expect a field-induced ordered state around the level crossing point, taking into account intersite interactions. For other field orientations, no crossing of the lowest levels is found in either scheme A or B. As a result, only scheme B offers an explanation for the high-field ordered state in a limited angular range around the [111] direction. We then performed numerical calculations using scheme B and a two-sublattice mean-field Hamiltonian including quadrupolar interactions: $H = H_0 + H_{\rm Q}$. Here, $H_{\rm Q}$ is the Γ_3-type quadrupolar interaction Hamiltonian, which can be given by $H_{\rm Q} = -K[\langle O_2^0\rangle_{\rm B(A)}O_2^0 + \langle O_2^2\rangle_{\rm B(A)}O_2^2]$, $O_2^0 = (3J_{\rm z}^2 - \mathbf{J}^2)/2$, and $O_2^2 = \sqrt{3}(J_{\rm x}^2 - J_{\rm y}^2)/2$. Figure 1(c) displays the calculated magnetization as functions of field at 0.5 K in the case of the coupling constant $K = -0.02$ K. In zero field, no ordered phase arises. Upon increasing the field, a second-order phase transition appears at 7 T, and the resulting phase diagram is given in Fig. 1(d). These calculations are qualitatively consistent with the experimental observation of phase B.

[1] T. Tayama *et al.*: J. Phys. Soc. Jpn. **73** (2004) 3258.
[2] Y. Aoki *et al.*: J. Phys. Soc. Jpn. **71** (2002) 2098.

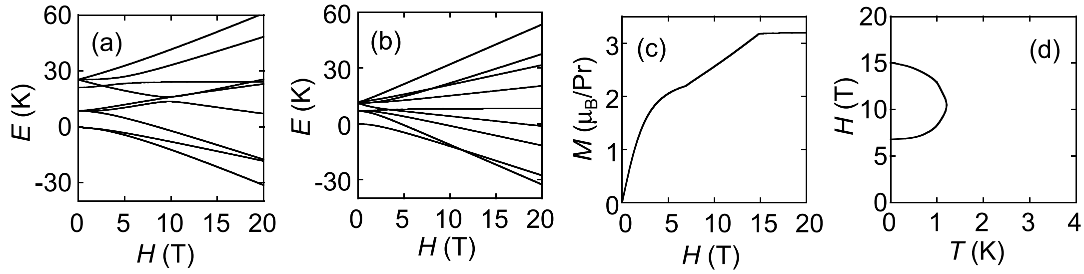

Figure 1: Energy of the crystal-field levels as a function of magnetic field along the [111] axis for scheme A (a) and B (b). Magnetization curve at 0.5 K (c) and the $H-T$ phase diagram (d) for scheme B.