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On the Field-Induced Ordered State in $PrOs_4Sb_{12}$
– Order Parameter and Dynamics –

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$PrOs_4Sb_{12}$ is a member of the filled-skutterudite compounds. The low-temperature phase diagram of this material consists of the superconducting phase in low fields and the field-induced ordered phase (FIOP) above 5T. Unusual properties of these two phases have raised much interest in this material. In this talk, we review our recent analysis on the FIOP [1,2,3] and discuss the meaning of recent experimental results. In particular, we focus on the basic question regarding the primary order parameter and elucidate the reason why the FIOP is considered to be of nonmagnetic origin.

Pr ions in filled skutterudites are believed to have a $4f^2$ configuration with a total angular momentum $J = 4$. The site symmetry is T_h, which is characterized by the absence of the four-fold symmetry axes. After some controversies, the crystal-field (CF) level scheme of $PrOs_4Sb_{12}$ is established as follows: The Γ_1 singlet is the CF ground state and a triplet, usually denoted as $\Gamma_4^{(2)}$, is located at $\sim$ 8K above the ground state. Since the T_h symmetry requires a complex mixture of multipolar moments, one should be careful to identify the order parameters, especially in magnetic fields.

In analogy with dimer-spin systems, we introduce two $S = 1/2$ pseudo-spins, with which Γ_1 and $\Gamma_4^{(2)}$ are regarded as the total-spin-zero state and the spin-one triplet. Using this representation, we clarify a hidden symmetry of multipolar interactions and the characteristic origin of the cubic anisotropy. We point out the importance of observed anisotropy for field directions in (i) the H-T phase diagram [4] and (ii) the structure of induce antiferromagnetic moment [5,6]. It is shown that these experimental results originate predominantly from nonmagnetic interaction.

Based on the symmetry properties and the mean-field solutions, we extend the analysis into the excitation and the inelastic neutron-scattering (INS) spectra. Although the dispersion of excitation energy exhibits a universal feature irrespective of the type of interaction, we show that the characteristic features of multipolar interaction appear in the scattering intensity. An important aspect of the quadrupolar interaction is that the intensity in low magnetic field exhibits a minimum at zone boundary, which is in contrast to the case for the interaction of magnetic multipoles. In this way, recent experimental results are interpreted as an evidence of the dominant quadrupolar interaction [7]. We will discuss also how the spectral shape of INS is changed with increasing magnetic field, reflecting the CF states and the order parameters.

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