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Competition between crystalline-electric-field singlet and exotic Kondo effects for Pr-based filled-skutterudites

K. Hattori and K. Miyake

Division of Materials Physics, Department of Materials Engineering Science, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan

An impurity model for Pr-based filled-skutterudites are proposed in order to explain their anomalous properties. Using numerical renormalization group method, we investigate an extended single impurity Anderson model which includes singlet Γ_1 and triplet Γ_4 as the f^2-states and Γ_7 and Γ_8 as the states for the conduction electrons under cubic symmetry. The system has a variety of fixed points depending on the relative strength of the hybridyzations v_{Γ_7} and v_{Γ_8}, and the crystalline-electric-field (CEF) splitting η. In particular, for the case of the parameter region relevant to $PrOs_4Sb_{12}$ (and possibly to $PrFe_4P_{12}$), i.e. f^2-Γ_1 ground state, there are two stable fixed points (or there is a critical point η_c): CEF singlet fixed point and the non-Fermi liquid (NFL) fixed point. The latter is the NFL which was investigated by Koga et al.[1] for the case without Γ_1 singlet and the Γ_7 conduction electron channel (also see for the related model[2][3]). At the NFL fixed point, the Sommerfeld coefficient γ is proportional to $T^{-2/3}$ and the residual f-electron entropy S_{imp} is about $0.9 k_B \log 2$. It is noted that even in the region $\eta \geq \eta_c$, γ is strongly enhanced if system is located near the critical point. We expect that this NFL criticality provides the origin of the heavy effective mass and the physics hidden behind the complexieties of the real systems for Pr-based skutterudites and the related other compounds.

[1] M. Koga, G. Zaránd and D. L. Cox, Phys. Rev. Lett. **83** (1999) 2421
[2] A. M. Sengupta and Y. B. Kim, Phys. Rev. B **54** (1996) 14918
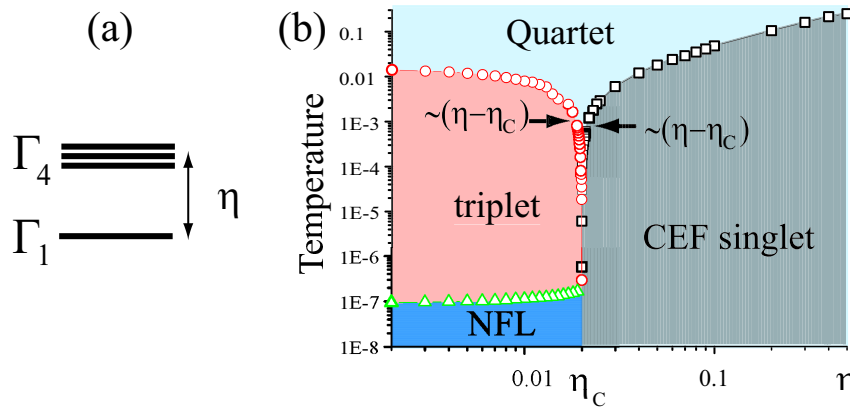[3] T. S. Kim, L. N. Oliveira and D. L. Cox, Phys. Rev. B **55** (1996) 12460

Figure 1: (a) The CEF configuration in f^2 manifold. (b) The CEF splitting η v.s. temperature "phase" diagram. All symbols ($\bigcirc, \triangle, \square$) represent cross over lines estimated by the entropy results in NRG calculations.The parameters used in this figure are $v_{\Gamma_7} = 0$ and $v_{\Gamma_8} = 0.3714$ in the unit of half the band width of conduction electron (v_{Γ_7} turns out to be irrelevant in the detailed analysis).