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## Crossover behavior in $\text{SmRu}_4\text{P}_{12}$

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One of the most intriguing behavior left unresolved among filled skutterudites is the understanding of the unusual magnetic field–temperature phase diagram of  $\text{SmRu}_4\text{P}_{12}$ . This compound shows a metal–insulator (MI) transition at  $T_{\text{MI}} = 16.5\text{K}$  which is followed by a subsequent anomaly at  $T^*$ . This anomaly shows up as a crossover in thermodynamic quantities, but it becomes sharper as the magnetic field is increased. NMR found that the ordered phase below  $T_{\text{MI}}$  is magnetic. However, the nature of the order parameter and the crossover behavior around  $T^*$  are unclear so far. Yoshizawa proposed the linear coupling between the dipole and octupole moments allowed in the  $T_h$  symmetry [1], which can give the crossover behavior of the lower transition at  $T^*$ .

We take Yoshizawa’s picture and study the crossover behavior due to the mixing of dipole and  $T^\beta$  octupole moments. The isotropy and the increase of the MI transition temperature in external magnetic field [2] suggests that  $\text{SmRu}_4\text{P}_{12}$  is close to the  $\text{SU}(4)$  interaction limit. Therefore, all multipolar interactions are important in the  $\Gamma_8$  quartet ground state. First, we consider the crossover behavior by phenomenological Landau analysis. It is shown that the crossover may change to first-order transition through a second-order transition point at a critical value of the external magnetic field if the linear coupling decreases with increasing magnetic field. Proceeding toward crystal field model, higher lying  $J = 7/2$  multiplet of  $\text{Sm}^{3+}$  is taken into consideration in addition to the  $J = 5/2$  ground state multiplet. In this way we take into account the  $T_h$  symmetry in the  $\Gamma_8$  quartet. It is found that the linear coupling between the dipole and  $T^\beta$  octupole moments caused by the  $T_h$  symmetry decreases with increasing magnetic field. This behavior can be responsible for the sharpening of the crossover at  $T^*$  as the magnetic field is increased. Renormalization of the linear coupling due to quadrupolar and  $T^\alpha$  octupolar interaction is obtained under finite magnetic field. Possible range for multipolar interactions in the  $\Gamma_8$  quartet is estimated and it is set against the  $\text{SU}(4)$  interaction limit.

## References

- [1] M. Yoshizawa et al., J. Phys. Soc. Jpn. **74** (2005) 2141.
- [2] D. Kikuchi et al., Journal of Magnetism and Magnetic Materials **310** (2007) e225.