

# Specific heat of heavy fermion compound $\text{CeRu}_2\text{Si}_2$ in magnetic field <sup>\*</sup>)

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The high field anomalies of the linear term in the specific heat of  $\text{CeRu}_2\text{Si}_2$  are shown to be caused by a reconstruction of the quasiparticle band due to the magnetostriction and by a destruction of short range magnetic order.

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## 1 Introduction

$\text{CeRu}_2\text{Si}_2$  is a “medium” heavy fermion system (HFS) with the electronic specific heat coefficient  $\gamma \approx 350 \text{ mJ mol}^{-1} \text{ K}^{-2}$ . A strong increase of magnetization is observed near  $H_m = 7.8 \text{ T}$  below 15 K (metamagnetic-like transition) [1]. The inelastic neutron experiments [2] revealed two types of magnetic correlations: a Kondo single site (elastic) and an intersite (short range) antiferromagnetic inelastic contribution, which is strongly quenched in the field above  $H_m$ . For high fields a long range static ferromagnetic response was found [3]. The coefficient  $\gamma$  of the linear term of the specific heat  $\gamma = c/T$ , shows a sharp peak at  $H_m$  for  $T = 0.25 \text{ K}$ . At higher temperatures, the peak in  $\gamma(H)$  changes into a double peak structure with a minimum at  $H_m$  and the distance between the peaks increasing monotonically with increasing temperature [4]. The de Haas–van Alphen experiments (dHvA) also indicate the peak structure around  $H_m$  in the field dependence of effective masses [5]. It was found that the value of  $\gamma$  derived from the dHvA data available ( $\gamma_{\text{qp}} = 260 \text{ mJ mol}^{-1} \text{ K}^{-2}$ ,  $T = 0$ ) well correlates with the thermodynamic Sommerfeld coefficient  $\gamma_{\text{th}}$ , but is by 25 % smaller. For fields above  $H_m$  this discrepancy becomes striking ( $\gamma_{\text{qp}}/\gamma_{\text{th}} \approx 0.2$  at 15 T). One of the possible explanation of the discrepancy is that also another degrees of freedom, not directly related to the quasiparticles, contribute to the anomalies of the specific heat. In [6] we pointed out the role of intersite fluctuations of the residual magnetic moments  $\mu_R \approx 0.5 \mu_B$  ( $\mu_B$  — Bohr magneton) resulting from incomplete Kondo screening (see [7]). In the following we illustrate the role of magnetic clusters in metamagnetic transition of  $\text{CeRu}_2\text{Si}_2$  and discuss the Kondo contribution.

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## 2 Quasiparticle contribution

We use the single-resonance-level model of Schotte and Schotte [7] which avoids explicit many body calculations by simulating the free energy of a Kondo system by a resonance of Lorentzian shape formed at the Fermi level with the width of resonance of order of the Kondo temperature  $T_K$ ,  $\Delta = kT_K$ . The resonance contribution to the free energy reads

$$F_{\text{qp}} = -kT \sum_{\sigma} \int_{-\infty}^{+\infty} \rho_{\sigma}(\varepsilon, H) \ln(1 + e^{-\varepsilon/kT}) d\varepsilon, \quad (1)$$

where the quasiparticle DOS for spin  $\sigma$  is

$$\rho_{\sigma}(\varepsilon, H) = \frac{\Delta(H)}{\Pi} \frac{1}{(\varepsilon - g\mu_B\sigma H_{\text{eff}})^2 + \Delta^2(H)}; \quad (2)$$

$g$  is the f-electron  $g$  factor and  $k$  the Boltzmann constant,  $\Delta$  is field dependent via the field dependence of the Kondo temperature. This in turn mainly results from magnetostriction [10]

$$T_K(H) = T_K(V) = T_K(0)e^{-\Gamma(V-V_0)/V_0}, \quad (3)$$

where  $V$  and  $V_0$  are the volumes for the field  $H$  and zero field and  $\Gamma$  is Grüneisen parameter  $\Gamma \equiv -\partial \ln T_K / \partial \ln V$ . The volume magnetostriction of CeRu<sub>2</sub>Si<sub>2</sub> has a peak around  $H_m$  [1] and  $\Gamma$  takes a huge value  $\approx 190$  [1], which enhances the volume effect by two orders of magnitude. Magnetostriction is expected to be the driving force of metamagnetic transition. In the region of transition also the strong field dependence of exchange interactions is observed [4]. For  $H > H_m$  ferromagnetic interaction starts to dominate (exchange interactions between quasiparticles [8])

$$H_{\text{eff}} = H + J(Q=0) \frac{m_{\text{qp}}}{\frac{1}{2}g\mu_B}. \quad (4)$$

$J(0)$  is the ferromagnetic, field dependent coupling [4] and  $m_{\text{qp}}$  is the quasiparticle magnetization i.e. total magnetization diminished by the residual moments contribution. Since around  $H_m$  all free residual moments (not belonging to AF clusters (60%) [2]) are oriented along the field, one can approximate  $m_{\text{qp}}$  by  $m - 0.6\mu_R$ . Using the experimental data of magnetostriction [1], magnetization [11] and the field dependence of ferromagnetic coupling [4] we have calculated the quasiparticle contribution to  $\gamma$ ,  $\gamma_{\text{qp}} = -\partial^2 F_{\text{qp}} / \partial T^2$  and the results are presented in Fig. 1. It is seen that the field-induced mass enhancement at  $H_m$  amounts to 1.21 at  $T = 1.3$  K. From the low-temperature magnetization measurements the enhancement of  $\gamma$  as large as 1.77 was deduced [1].

## 3 Residual magnetic moments contribution

Part of the residual magnetic moments is bound in small AF clusters (40%). At  $H_m$  the short range magnetic correlations are suppressed [2]. For simplicity, we

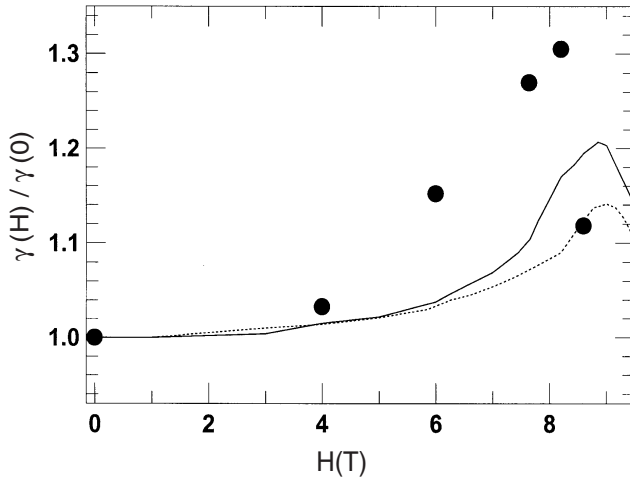


Fig. 1. Field dependence of the coefficient  $\gamma$  of the linear term in the specific heat for  $\text{CeRu}_2\text{Si}_2$ . Solid and broken lines are the calculated quasiparticle contributions for  $T = 1.3 \text{ K}$  and  $T = 4.2 \text{ K}$ , respectively. Experimental data ( $T = 1.5 \text{ K}$  [12]) are shown by dots.

illustrate the resulting contribution to  $c/T$  by considering the clusters consisting of a central site and its four nearest neighbours. The Ising form of interaction is assumed, which is justified by the strong anisotropy of  $\text{CeRu}_2\text{Si}_2$  [2].

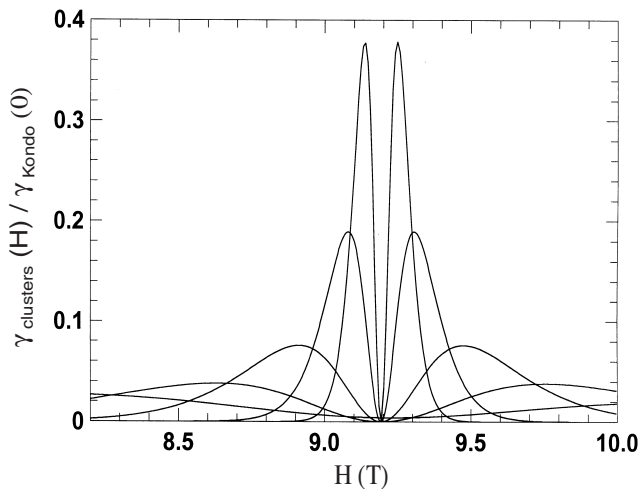


Fig. 2. Field dependence of the magnetic clusters contribution to  $\gamma$  close to metamagnetic transition for  $T = 0.05, 0.1, 0.25, 0.5$  and  $1 \text{ K}$  (the curves from top to bottom).

The specific heat of a cluster reads:

$$c = \frac{1}{kT^2} \frac{\sum_{\{S\}} (E_S^2 e^{-\beta E_S}) \left( \sum_{\{S\}} e^{-\beta E_S} \right) - \left( \sum_{\{S\}} E_S e^{-\beta E_S} \right)^2}{\left( \sum_S e^{-\beta E_S} \right)^2}, \quad (5)$$

where  $\beta = 1/kT$  and spin configuration  $\{S\}$  for the 5-site cluster denotes  $\{S\} = \{(S_1, S_2 \dots S_5)\}$ ,  $S_i = \pm \frac{1}{2}$ ,  $E_S = JS_1 \sum_{i=2}^5 S_i + 2h_{\text{eff}}\mu_R \sum_{i=1}^5 S_i$ ,  $h_{\text{eff}} = H - 3J_{\text{AF}}(H)\mu_R$ .  $J_{\text{AF}}(H)$  is estimated from the antiferromagnetic coupling  $J(Q = k, H)$ ,  $k = (0.31, 0.31, 0)$  given in [3].  $J(k) = \sum_{\delta} J_{\text{AF}} e^{ik\delta}$  with  $\delta$  running over nearest neighbours. Figure 2 presents the temperature evolution of  $c/T$  for the independent spin clusters with  $J = J_{\text{AF}}(H = 0) = 0.25 \text{ meV}/\mu_B^2$  [3]. Remarkable is the temperature dependent splitting of the peak which is also observed in experiment [4].

In summary, the present communication points out two sources of anomalies observed near metamagnetic transition, one resulting from the narrowing and shift of heavy quasiparticle band due to magnetostriction effect and field induced exchange interactions and another due to the destruction of small AF clusters formed by residual magnetic moments.

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## References

- [1] A. Lacerda, A. de Visser, P. Haen et al.: Phys. Rev. B **40** (1989) 8759.
- [2] J. Rossat-Mignod, L.P. Regnault, J.L. Jacoud et al.: J. Magn. Magn. Mater. **76/77** (1988) 376.
- [3] S. Raymond, D. Raelison, S. Kambe et al.: Physica B **261** (1999) 48.
- [4] Y. Aoki, T.D. Matsuda, H. Sugawara et al.: J. Magn. Magn. Mater. **171–181** (1998) 271.
- [5] H. Aoki, S. Uli, A.K. Albessand et al.: J. Phys. Soc. Jpn. **62** (1993) 3157.
- [6] S. Lipiński: J. Magn. Magn. Mater. **170** (1997) L248.
- [7] P. Nozières: Eur. Phys. J. B **6** (1998) 447.
- [8] H. Satoh and F. Ohkawa: Phys. Rev. B **57** (1998) 5891.
- [9] K.D. Schotte and U. Schotte: Phys. Lett. A **55** (1975) 38.
- [10] F.J. Ohkawa: Solid State Commun. **71** (1989) 907.
- [11] M.J. Besnus, J.P. Kappler, P. Lehmann, and A. Mayer: Solid State Commun. **55** (1985) 779.
- [12] A. de Visser, J.J.M. Franse, and J. Flouquet: J. Magn. Magn. Mater. **108** (1992) 15.