NON-FERMI-LIQUID FEATURES OF NOVEL Yb$_2$Pd$_2$In*

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Yb in ternary Yb$_2$Pd$_2$In exhibits a valency $\nu \approx 2.9$ and consequently, no clear evidence of long range magnetic order down to 40 mK. Low temperature resistivity and specific heat are characterized by significant deviations from a Fermi-liquid (FL) scenario. While the application of magnetic fields recovers a FL state, pressure drives the system closer to a magnetic instability at $T = 0$.

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Heavy fermion compounds close to a magnetic instability at $T_{\text{mag}} = 0$ can be driven across a quantum critical point (QCP) by varying non-thermal parameters like chemical substitution, pressure or magnetic fields. Next to such a quantum critical regime a number of extraordinary properties are observable, see e.g. Refs. [1,2].

Several features make Yb compounds attractive to study low temperature anomalies; among them is the tuning of properties by alloying or pressure, which responds in most cases in a mirror-like manner when compared to Ce compounds. While for Yb compounds the parameters $JN(E_F)$ and

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$T_K$ decrease upon increasing pressure, the opposite happens for Ce compounds. For that reason, pressure drives Yb systems towards the magnetic regime and possibly, the QCP is crossed from the non-magnetic side [3,4]. In the present paper we aim to evaluate low temperature properties of crystallographically ordered ternary Yb$_2$Pd$_2$In. For the synthesis and crystal structure see Ref. [5].

In order to examine the possibility of magnetic ordering in Yb$_2$Pd$_2$In, Mössbauer spectra on the isotope$^{170}$Yb were recorded down to 40 mK. Results of the 40 mK run are shown in Fig. 1(a). Spectra taken at 4.2 K and 40 mK are identical, and correspond to a quadrupolar hyperfine interaction alone, i.e. no hyperfine magnetic field is present. This shows that no magnetic ordering of the Yb$^{3+}$ moments is present at this temperature, with moments larger than 0.05 $\mu_B$. A least squares fit to the data (solid line, Fig. 1(a)), taking into account a non-axial quadrupolar hyperfine hamiltonian, reveals for the quadrupolar coupling parameter $\alpha_Q = 1.85$ mm/s, and for the asymmetry parameter $\eta = 0.4$, values typical for a paramagnetic Yb$^{3+}$ ion at a site with non-axial symmetry.

![Figure 1](image_url)

**Fig. 1.** (a) $^{170}$Yb Mössbauer spectrum of Yb$_2$Pd$_2$In taken at 40 mK. The solid line is a least squares fit (see text). (b) $I_{III}$ absorption spectra of Yb$_2$Pd$_2$In at $T = 300$ and 10 K. The solid line is a least squares fit.

The absence of magnetic order in Yb$_2$Pd$_2$In can be also concluded from X-ray absorption edge data. Results of $I_{III}$ measurements taken at $T = 10$ and 300 K, together with a standard analysis, are displayed in Fig. 1(b). The valency of the Yb ion thus derived is $\nu = 2.89$, showing only insignificant temperature dependence. There is experimental evidence that already a slight drop of the valency from 3 causes a vanishing of magnetic order.
in Yb systems (see e.g., Yb(Cu,Al)₅ [4]). Thus, Mössbauer and $I_{\text{III}}$ data consistently prove a non-magnetic ground state in Yb₂Pd₂In. Moreover, the effective magnetic moment $\mu_{\text{eff}} = 3.88 \, \mu_B$/Yb, deduced from a Curie-Weiss like susceptibility for $T > 30$ K, is well below that of Yb$^{3+}$, which also makes magnetic order rather unlikely.

The overall shape of $\rho(T)$ (Fig. 2(a),(b)) is in line with a typical Kondo lattice: At high temperatures, the logarithmic contribution to $\rho(T)$ indicates incoherent Kondo scattering. The maximum at $T_{\text{max}}^\rho \sim T_K$ roughly measures the Kondo temperature [6] and the decrease of $\rho(T)$ below $T_{\text{max}}^\rho$ indicates coherent scattering. The pressure response of $\rho(T)$, Fig. 2(a), is characterised by three distinct features: (i) $T_{\text{max}}^\rho$ lowers significantly from about 60 K ($p = 1$ bar) to below 30 K ($p = 16$ kbar) at an initial rate of $\partial T_{\text{max}}^\rho / \partial T = -2.4 \, \text{K/kbar}$. (ii) The low temperature slope of $\rho(T)$ increases. (iii) The analysis of these data yields a huge Grüneisen parameter $\Gamma_\rho = -42$, reflecting a strong volume dependence of various physical quantities.

![Graph showing electrical resistivity $\rho(T)$ for Yb₂Pd₂In](image)

Fig. 2. (a) Electrical resistivity $\rho(T)$ of Yb₂Pd₂In for various values of pressure. The inset shows the pressure dependent variation of the exponent $n$. (b) Electrical resistivity $\rho(T)$ of Yb₂Pd₂In for various values of applied fields. The inset shows low temperature details and the solid lines are least squares fits.

The low temperature behaviour of $\rho(T)$ is accounted for in terms of $\rho = \rho_0 + AT^n$ where $\rho_0$ is the residual resistivity; an exponent $n = 2$ would reflect a Fermi liquid behaviour of the system. Least squares fits to the low temperature data, however, indicate a substantially lower value of $n \approx 1.4$ at ambient pressure and as $p$ increases, a decrease of $n$ is derived with $n \approx 1$ for $p = 16$ kbar being indicative for non-Fermi-liquid behaviour. The evolution of $n(p)$ most likely indicates a shift towards the QCP of the system, and beyond the present pressure range long range magnetic order is expected.
The field dependence of $\rho(T)$, Fig. 2(b), is characterised by (i) an increase of $T^\text{max}_\rho$ with growing fields and (ii) an increase of $n$ approaching $n \approx 2$ for 12 T. The latter reflects the quenching of critical magnetic fluctuations and hence a Fermi-liquid behaviour is supposed to be recovered.

The temperature dependent specific heat of Yb$_2$Pd$_2$In is shown in Fig. 3 together with that of isomorphous non-magnetic La$_2$Pd$_2$In. Magnetic entropy is deduced from the difference of both samples and the continuous increase evidences that entropy release is spread over a broad temperature range due to Kondo interaction. Yb$_2$Pd$_2$In exhibits at $T \approx 2.2$ K a small anomaly in $C_p/T$ due to traces of magnetically ordered Yb$_2$O$_3$. Below 2 K, $C_p/T$ increases logarithmically, but levels off around 0.5 K. With increasing magnetic fields (not shown here), this feature is even shifted to higher temperatures. In view of the Mößbauer results, such a structure cannot be attributed to magnetic ordering, but may reflect a particular energy dependence of a non-Fermi-liquid ground state. Moreover, the shape of $C_p(T)$ around 500 mK does not resemble a typical spin glass.

In summary, Yb$_2$Pd$_2$In does not show long range magnetic order above 40 mK. Pressure and field dependent resistivity, as well as specific heat measurements rule out a simple Fermi-liquid ground state.

![Figure 3](image)

Fig. 3. Temperature dependent specific heat $C_p$ plotted as $C_p/T$ vs $T$ of Yb$_2$Pd$_2$In and La$_2$Pd$_2$In. The solid line is a fit to the Debye model; magnetic entropy refers to the right axis. The inset shows low temperature features in Yb$_2$Pd$_2$In.

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