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SLOW CROSSOVER AND OBSERVATION OF A SECOND ENERGY SCALE IN YbAl$_3$*

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YbAl$_3$ is an intermediate valent compound with a large Kondo temperature $T_K$ and moderately low conduction electron density. Because of this, YbAl$_3$ is a prime candidate for the observation of effects caused by low conduction electron density, where coherence sets in below $T_{coh}$ rather than $T_K$ ($T_{coh} \ll T_K$). For the first time, we have directly observed the crossover between the energy scales by the application of a magnetic field above $B^* \approx 40$ T ($\approx k_BT_{coh}/\mu_B$). We also observe a reduction in the effective masses above $B^*$ that is consistent with the energy scale crossover.

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1. Introduction

YbAl$_3$ is an intermediate valent (IV) compound with a Kondo temperature $T_K$ in excess of 500 K and a moderately low conduction electron density of $n_c \sim 0.5$/atom [1]. Recent theoretical studies [2, 3] of the Anderson Lattice Model (ALM) suggest that the thermodynamic properties can differ in at least two ways from the predictions of the Anderson Impurity Model

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(AIM). As the background conduction electron density $n_e$ decreases, theory predicts [3] a new low temperature scale $T_{coh}$ for the onset of Fermi liquid coherence with $T_{coh} \ll T_K$ along with a crossover from low temperature Fermi liquid behavior to high temperature local moment behavior slower than predicted for the AIM [2]. We report data on YbAl$_3$ which shows that an applied field of 40 T causes an energy scale crossover from $T_{coh}$ to $T_K$ and a reduction in the effective masses relative to the low field values [4].

2. Results

Thermodynamic measurements have been reported elsewhere [1]. First, the crossover from low temperature Fermi liquid behavior to high temperature local moment behavior is slower than predicted for the AIM. Second, anomalies (relative to the AIM) occur below 30-40 K, which is the temperature scale $T_{coh}$ for the onset of coherent Fermi liquid $T^2$ behavior in the resistivity. We believe that these effects are generic to IV compounds, as a slow crossover exists in a number of YbXCu$_4$ compounds [5] and a small coherence scale is observed in CePd$_3$ [6]. The occurrence of the slow crossover and the low energy scale in YbAl$_3$ and other IV compounds correlates with a low background conduction electron density [1].

The magnetization and dHvA effect were measured up to 60 T as described elsewhere [1]. Fig. 1 shows the magnetization as a function of applied magnetic field at temperatures above and below $T_{coh}$ $\approx$ 40 K. The solid lines are linear fits to the data in the magnetic field range 10 T $< B < 35$ T. The difference between the linear fits and the raw data is shown in the inset. At both temperatures, the data display linear behavior for $B < 40$ T. Above

![Fig. 1. Magnetization measurements in pulsed magnetic fields to 60 T at 4 K and 110 K. The solid lines are fits to the data below 35 T. The inset shows the difference between the measured values and the linear fit.](image-url)
40 T, there is a clear change in slope for the 4 K data while the 110 K data retains its linearity. As the slope is simply the magnetic susceptibility \( \chi \), there is clearly a reduction in \( \chi \) above 40 T at 4 K. A detailed examination of the temperature dependence of the low field (\( B < 35 \) T) data is in good agreement with SQUID measurements which show two maximum in \( \chi(T) \) indicative of two energy scales, while the high field (\( B > 40 \) T) data shows a single maximum which is consistent with a single energy scale \( T_K \) [1].

Fig. 2 shows results for the dHvA measurements for \( B \parallel (111) \). As can be seen, all four branches (labelled \( \beta, \eta, \alpha \) and \( \varepsilon \)) observed in previous low field (\( B < 17 \) T) measurements [4] are also observed in the 60 T pulsed field measurements. The frequencies \( F \) as given in Fig. 2 are found to be relatively unchanged compared to the values found in low fields, indicative of no fundamental change occurring in the shape of the Fermi surface at \( B^* \). The effective masses \( m^* \), however, are all found to be reduced up to a factor of three and are found to be independent of field above \( B^* \). This reduction in \( m^* \) is consistent with the drastic change in the energy scales as one finds that \( m^* \) should scale as the inverse of the relevant energy scale.

![Diagram](image)

**Fig. 2.** Effective masses \( m^* \) *versus* average applied magnetic field \( B_{av} \) for \( B \parallel (111) \) in YbAl3. Four branches are observed with labelling and frequencies \( F \) the same as in Ref. [4]. The different symbols represent measurements on two separate crystals. The solid lines show the values of \( m^* \) measured for \( B < 17 \) T from Ref. [4].
YbAl₃ is an IV compound with a moderately low conduction electron density which is found to have two energy scales T_{coh} \approx 40 \text{ K} and T_K \approx 600 \text{ K}. For T \ll T_{coh} we find that the magnetization ‘crosses’ over from the zero field energy scale T_{coh} to the high temperature energy scale T_K at a magnetic field B' \approx 40 \text{ T} (= k_B T_{coh}/\mu_B) with little change in the shape of the Fermi surface however the effective masses are all reduced relative to their low field values [4]. This is the first direct observation of the crossover between the T_{coh} and T_K energy scales as a function of magnetic field in an IV compound.

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