Vol. 34 (2003) *ACTA PHYSICA POLONICA B* No 2

SLOW CROSSOVER AND OBSERVATION OF A SECOND ENERGY SCALE IN $YbAl_3$*

A.L. Cornelius

Department of Physics, University of Nevada, Las Vegas
4505 S. Maryland Parkway, Las Vegas, Nevada, 89154-4002, USA

T. Ebihara

Department of Physics, Faculty of Science, Shizuoka University
836 Ohya, Shizuoka 422-8529, Japan

and J.M. Lawrence

Department of Physics and Astronomy, University of California
Irvine, CA 92697, USA

(Received July 10, 2002)

$YbAl_3$ 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 cross over between the energy scales by the application of a magnetic field above $B^* \approx 40$ T ($\approx k_B T_{coh}/\mu_B$). We also observe a reduction in the effective masses above B^* that is consistent with the energy scale crossover.

PACS numbers: 75.30.Mb, 75.20.Hr, 71.27.+a, 71.28.+d

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

---

[*] Presented at the International Conference on Strongly Correlated Electron Systems, (SCES 02), Cracow, Poland, July 10–13, 2002.

(AIM). As the background conduction electron density n_c 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

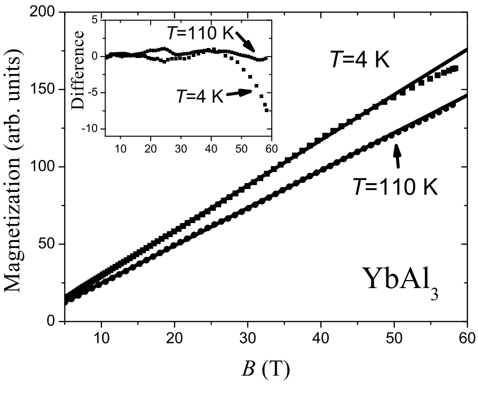

Fig. 1. Magnetization measurements in pulsed magnetic fields to 60 T at 4 K and 110 K. The solid lines are fits to the data below 35 T. The inset shows the difference between the measured values and the linear fit.

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 χ, there is clearly a reduction in χ 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 $B||(111)$. As can be seen, all four branches (labelled β, η, α and ε) 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.

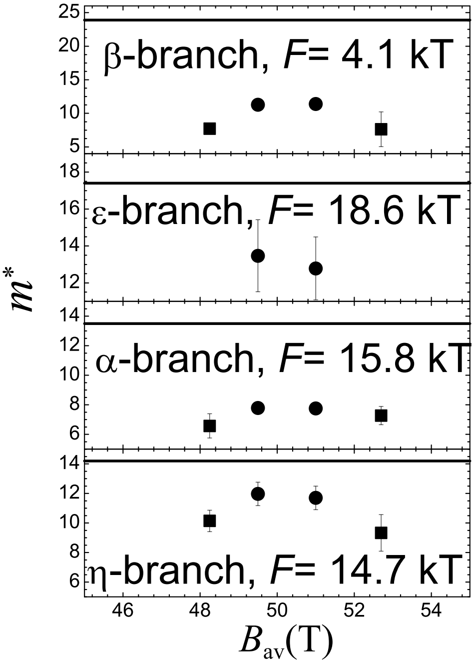

Fig. 2. Effective masses m^* *versus* average applied magnetic field B_{av} for $B||(111)$ in $\mathrm{YbAl_3}$. Four branches are observed with labelling and frequencies F the same as in Ref. [4]. The different symbols represent measurements on two separate crystals. The solid lines show the values of m^* measured for $B < 17$ T from Ref. [4].

$YbAl_3$ is an IV compound with a moderately low conduction electron density which is found to have two energy scales $T_{\rm coh} \approx 40$ K and $T_{\rm K} \approx 600$ K. For $T \ll T_{\rm coh}$ we find that the magnetization "crosses" over from the zero field energy scale $T_{\rm coh}$ to the high temperature energy scale $T_{\rm K}$ at a magnetic field $B^* \approx 40$ T ($\approx k_{\rm B}T_{\rm coh}/\mu_{\rm B}$) 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 $T_{\rm coh}$ and $T_{\rm K}$ energy scales as a function of magnetic field in an IV compound.

Work at UNLV was supported by DOE Award DE-FG02-00ER45835. Work at UC Irvine was supported by UCDRD funds provided by the University of California. T. E. acknowledges the support of the Japanese Ministry of Education.

REFERENCES

[1] A.L. Cornelius, J.M. Lawrence, T. Ebihara, P.S. Riseborough, C.H. Booth, M.F. Hundley, P.G. Pagliuso, J.L. Sarrao, J.D. Thompson, M.H. Jung, A.H. Lacerda, G.H. Kwei, *Phys. Rev. Lett.* **88**, 11702 (2002).

[2] A.N. Tahvildar-Zadeh, M. Jarrell, J.K. Freericks, *Phys. Rev.* **B55**, R3332 (1997); *Phys. Rev. Lett.* **80**, 5168 (1998).

[3] S. Burdin, A. Georges, D.R. Grempel, *Phys. Rev. Lett.* **85**, 1048 (2000).

[4] T. Ebihara, Y. Inada, M. Murakawa, S. Uji, C. Terakura, T. Terashima, E. Yamamoto, Y. Haga, Y. Ōnuki, H. Harima, *J. Phys. Soc. Jpn.* **69**, 895 (2000).

[5] J.M. Lawrence, P.S. Riseborough, C.H. Booth, J.L. Sarrao, J.D. Thompson, R. Osborn, *Phys. Rev.* **B63**, 054427 (2001).

[6] J.M. Lawrence, Y.-Y. Chen, J.D. Thompson, *Theoretical and Experimental Aspects of Valence Fluctuations and Heavy Fermions*, eds. L.C. Gupta, S.K. Malik, Plenum Press, New York 1987, p. 169.