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Non-Fermi liquid behaviour in UCoAl: Pressure variations

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Abstract

The band metamagnet UCoAl was found to exhibit non-Fermi liquid scaling of electrical resistivity. In this contribution, we describe resistivity data on UCoAl single crystal obtained under extreme conditions. We demonstrate that a $bT^{5/3}$ term extends to temperatures below 0.5 K and that very high pressure (>5 GPa) is necessary to drive UCoAl to the Fermi liquid regime.

Keywords: Non-Fermi liquid; Band metamagnetism

1. Introduction

One of interesting phenomena occurring at the verge of magnetic ordering is band metamagnetism. Band metamagnets remain paramagnetic in low-magnetic fields, but if the field exceeds a critical field H_c, they resemble ferromagnets with spontaneous magnetic moments. Archetypes of such behaviour are YCo_2 and $LuCo_2$, with the critical metamagnetic field approaching 100 T. Although UCoAl exhibits a striking similarity of the phenomenology (as, e.g. the critical field H_c, increasing quadratically with temperature), its characteristic energy scale is curiously low 0.65 T, and the metamagnetism appears only if the field is applied along the hexagonal *c*-axis. Magnetization in the high-field state is relatively low, 0.35 μ_B/U atom, but there are larger spin and orbital moments oriented antiparallel [1–3].

UCoAl, crystallizing in the hexagonal structure (ZrNiAl structure type), can be globally characterized as spin fluctuator, with a broad knee in the temperature dependence of electrical resistivity around $T = 80$ K with a weak tendency to saturation at higher temperatures. Fig. 1 shows that there is a certain anisotropy, but the type of dependence does not differ for the two principal current directions, *i*//*c* and *i*//*a*. At low *T*, below about 20 K, $\rho(T)$ was reported to exhibit a non-Fermi liquid (NFL) scaling bT^n, with $n = 5/3$ [4,5] for both current directions. The conjecture that this feature is due to spin fluctuations on the non-magnetic side of a critical point is corroborated by the fact that the resistivity transforms to the conventional aT^2 above the metamagnetic transition. One deals in this case with a "light" Fermi liquid, observable because other low-lying excitations are missing (magnons absent due to the strong uniaxial anisotropy).

UCoAl is, though, rather different compared to the most common NFL systems, which are not based on band metamagnetism. (For overview, see Ref. [6].) This explains, why no special low-*T* features of magnetic susceptibility, like a strong monotonous increase, are not found in UCoAl. For this compound, susceptibility is dominated, similar to other band metamagnets, by a rounded maximum, located around $T = 20$ K (see Fig. 2). Also specific heat exhibits an additional term below this temperature, but it is relatively weak and masked by a large contribution of the nuclear specific heat below about 1.5 K ($\gamma \approx 72$ mJ/mol K^2 without the nuclear quadrupolar contribution). Therefore, electrical resistivity represents the most essential diagnostic tool.

The situation of UCoAl can be tentatively mapped on a standard schematic phase diagram with magnetism vanishing at a quantum critical point, and further tuning away from the magnetic regime establishes the Fermi liquid (FL) state,

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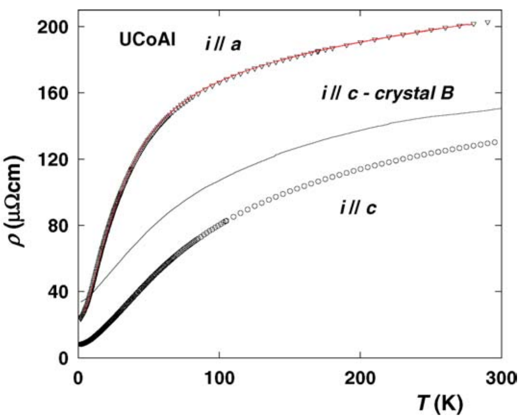

Fig. 1. Temperature dependence of electrical resistivity for different current directions, compared with results on a single crystal of lower purity (*i*//*c*). Data for the single crystal B, which was prepared by mineralization technique and which has a worse quality, are shown for a comparison.

extending gradually to higher temperatures. Assuming the validity of this picture, the FL regime should emerge at very low temperatures below the NFL regime (unless UCoAl in the ground state is accidentally exactly at the quantum critical point, which we suppose as implausible).

Therefore, we decided to extend the temperature range of the measurement below 1 K. Furthermore, as UCoAl is sensitive to hydrostatic pressure, which moves fast the critical metamagnetic field toward higher values and the high-field magnetization is reduced [2,7], we may assume that pressure tuning UCoAl towards the FL regime (increasing 5f–5f overlap increases the 5f band width and reduces the density of states at the Fermi level) will act rapidly by the suppression of the NFL state. Surprizingly, preliminary high-pressure resistivity studies indicated that the NFL character remains preserved in the pressure range up to 2.2 GPa, only the prefactor is gradually reduced [8]. Here, we describe results of detailed resitivity studies, capturing the transformation to the FL regime on the pressure scale up to 10 GPa. The goal of the present study is to analyze, whether the NFL character is intimately connected with the metamagnetism in UCoAl, and if it will be replaced by the Fermi liquid resistivity aT^2 once the metamagnetism vanishes. A fundamental issue is also the way of the crossover between the two regimes—we may expect either the value of n growing gradually from 5/3 to 2 or as canonical phase diagram suggests, the FL phase should exist at lower temperatures and spread gradually into the NFL temperature range. Here, we present results of resistivity studies on a single crystal of UCoAl, performed for current *i*//*a*-axis, in pressures up to 10 GPa. Preliminary data obtained for *i*//*c* (not shown here) exhibit the same tendency.

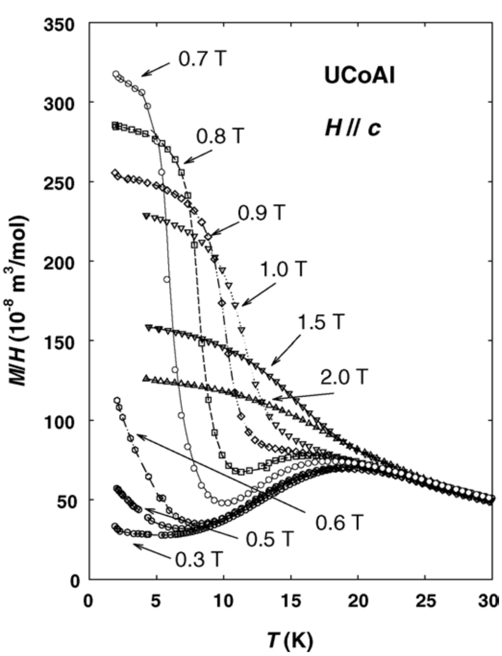

Fig. 2. Temperature dependence of magnetic susceptibility M/H for different values of magnetic field H. Lines are guides to the eye.

2. Experimental results and discussion

Electrical resistivity was studied on different pieces of the single crystal prepared in a tetra-arc furnace from pure metals of at least 3N purity, which was used in previous studies [4,5,7]. A good quality of the crystal can be deduced by the comparison with the crystal B, prepared by a mineralization technique, which has a significantly higher residual resistivity.

High-pressure measurements have been performed at ITU Karlsruhe, using a four-probe DC technique with the sample and a piece of lead (manometer) pressed in a piston-cylinder device, with steatite as a pressure-transmitting medium.

Because resistivity of UCoAl has not been so far studied for temperatures below 1 K, we could not a priori assume that the NFL scaling extends to the millikelvin range. Therefore, prior to high-pressure studies we used the experimental setup in the low-pressure range ($p < 1$ GPa) with emphasis on low temperatures. We found the NFL behaviour with the exponent $n = 5/3$ to extend from ≈12 K down to the lowest temperature achieved, i.e. 0.45 K.

The pressure was subsequently gradually increased, and at each pressure the resistivity was measured in the temperature range 1.2–300 K, in selected cases down to 0.5 K. The variations of global $\rho(T)$ features are seen in Fig. 3. Besides resistivity variations in the high-temperature range, which can be understood as the increase of the characteristic temperature of spin fluctuations, shifting the knee towards higher temperatures and partly suppressing it, the figure also indicates changes of the low-temperature part, seen better in Fig. 4. Four-different regimes of resistivity can be recognized:

- In the low-pressure range ($p < 5$ GPa), the NFL type can be found in the whole temperature range up to about 20 K. It means that $n = 5/3$ is preserved, but the prefactor is reduced gradually with increasing p.

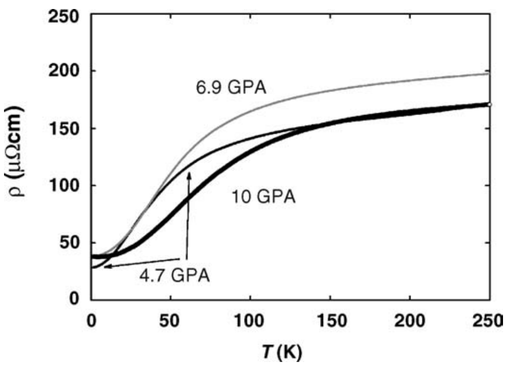

Fig. 3. Temperature dependence of electrical resistivity, obtained for selected pressures around the NFL–FL transition.

- Roughly around $p = 5$ GPa, the FL ($n = 2$) character spreads gradually from the low-T end and consumes the NFL range. Particularly, the pressure $p = 4.7$ GPa still exhibits the $n = 5/3$ character down to the low-T limit, for $p = 5.3$ GPa, $n = 2$ is clearly observable up to at least 10 K, while a short $n = 5/3$ part can be distinguished above this temperature range. Residual resistivity increases.
- For p around 6 GPa, the NFL part vanishes completely, the a-value of 0.07 $\mu\Omega\,\mathrm{cm\,K^{-2}}$ corresponds (using the Kadowaki–Woods relation) to 83 mJ/mol K^2.
- In the range 7–10 GPa, pressure leads to a rapid reduction of a and $a = 0.02$ $\mu\Omega\,\mathrm{cm\,K^{-2}}$ in $p = 8.5$ GPa. The high-temperature knee, located around 80–100 K, attributed to spin fluctuations, is shifted to higher T and smeared out, ρ decreases, UCoAl tends to a "normal metal" character.

Let us consider in more detail the impact of hydrostatic pressure on UCoAl. Magnetization studies, performed for pressures up to 1.2 GPa [7] indicate increase of the critical metamagnetic field and decrease of the increment of magnetization at the transition, both approximately linear as a function of p. On the other hand, pressure is only an implicit variable, as properties are in reality tuned by the variations of volume. From the point of view of bonding properties, UCoAl does not differ from other U ternaries crystallizing in the ZrNiAl structure type with a specific 5f bonding perpendicular to the c-axis. While the compression along c is weak and linear function of pressure, much softer a-axis leads also to a pronounced non-linearity, studied on the pressure scale to 50 GPa, but bringing a non-negligible effect in smaller pressures already [9].

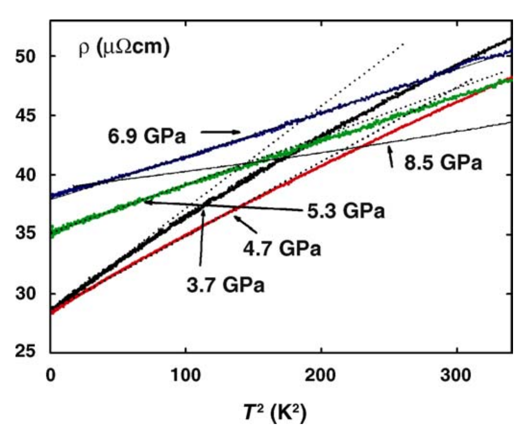

Fig. 4. Electrical resistivitiy ρ vs. T^2 for UCoAl single crystal, $i//a$ for various pressures around the crossover of the low-temperature scaling. The general downturn curvature for the lowest pressure (3.7 GPa) is the fingerprint of the NFL scaling. Analysis reveals that the exponent 5/3 holds in this pressure range. For the next pressure point, $p = 4.7$ GPa, the FL character is spread from the lowest temperatures up to about 12 K. At $p = 5.3$ GPa, the NFL character is practically suppressed. The dotted straight lines represent a reference for assessing how the data follow the T^2 law. Data for the highest pressure, $p = 8.5$ GPa, are represented by a solid line.

The increment of magnetization at the metamagnetization transition is reflected in a magnetostriction effect (a expands by the factor of 1.6×10^{-4}, c contracts by 1.33×10^{-4}, both at $T = 2$ K). The overall volume effect is positive: $\Delta V/V = 1.87 \times 10^{-4}$). Comparing pressure variations of the magnetostriction effect (reduction with increasing pressure) with the respective magnetization increment, we found that $\Delta a/a$ is proportional to $(\Delta M)^2$, i.e. the standard expression for itinerant magnetism, $\Delta V/V \sim (\Delta M)^2$ is modified in this case. Extrapolation to higher pressures gives an estimated $\Delta a = 0$, implying $\Delta M = 0$, i.e. the suppression of metamagnetism, at the volume corresponding to the hydrostatic pressure approximately 6 GPa. In reality, such situation cannot be achieved due to the fast increase of the critical metamagnetic field with increasing pressure.

The variations of electrical resistivity with pressure, in particular the fact that the FL character sets in quite abruptly in the pressure range of the complete suppression of metamagnetism, strongly suggest that the NFL behaviour is an intrinsic characteristic of the low-field phase, which can undergo the metamagnetic transition. It emphasizes the role of magnetic fluctuations in the metamagnetic behaviour. Consequently, the phase diagram of UCoAl exhibits a non-Fermi liquid "phase" spreading down to the baseline over a considerable pressure range, not only at a quantum critical point (see Fig. 5).

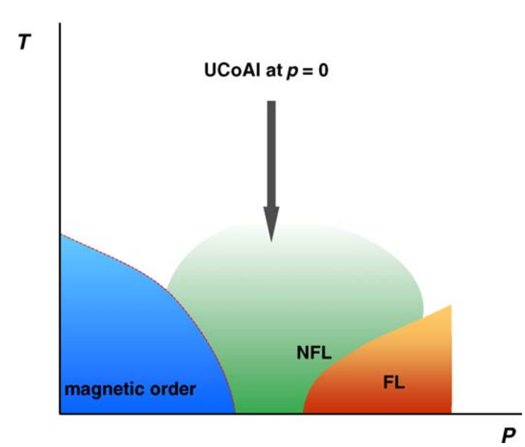

Fig. 5. Schematic phase diagram describing the situation of UCoAl. Hydrostatic pressure drives UCoAl from the position of the arrow to the right and the FL phase emerges rather abruptly around 5 GPa. On the other hand, negative pressure can lead to the onset of ferromagnetism stable at $H = 0$ [10].

3. Conclusions

As a conclusion, we confirmed that the band metamagnet UCoAl is a specific type of undoped material with the NFL resistivity scaling over a large temperature range. Its NFL character is suppressed only at extreme pressures, which are necessary to suppress the band metamagnetism.

Acknowledgements

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