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PRESSURE DEPENDENCE OF THE SUSCEPTIBILITY AND RESISTIVITY OF THE HEAVY-FERMION SUPERCONDUCTOR UPt_3

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The normal-state low-temperature anomalies of the heavy-fermion superconductor UPt_3 are characterized by a degeneracy temperature of about 10 K. The pressure dependence of this temperature has been studied in susceptibility and resistivity measurements under pressures up to 4.5 kbar. These results are compared with forced magnetostriction, specific heat and thermal expansion data.

1. Introduction

The state of localization of the 5f electrons in actinide metals is a matter of growing interest. Superconductivity in uranium intermetallics is more frequently observed at smaller values for the distance between neighbouring uranium atoms in contrast to magnetic order for which the opposite holds. This observation suggests a suppression of magnetic order and an enhancement of superconductivity with increasing pressure. In the limit of localized 5f electrons, pressure effects on the spontaneous magnetic moment are found to be extremely weak, whereas in the itinerant case, magnetism is indeed suppressed with increasing pressures. For the superconducting intermetallic uranium compounds, however, positive as well as negative pressure effects on the superconducting transition temperature have been reported [1–6].

Several of the uranium intermetallics combine superconductivity with extremely large values for the coefficient of the electronic term in the specific heat. A prominent example is UPt_3, for which compound high-pressure data are available in the superconducting and normal state. The high-pressure data include the pressure effects on resistivity and susceptibility in the normal state, besides data on the superconducting transition and the temperature dependence of the upper critical field [5–8]. Superconductivity in UPt_3 is a bulk property as Meissner experiments prove [9]. Nevertheless, the transition temperature is extremely sensitive to stresses and/or defects and to small amounts of non-magnetic impurities [10, 11]. This has led to speculations on triplet superconductivity and on electron pairing otherwise than by electron–phonon interactions.

By discussing the heavy-fermion superconductors in an almost-localized Fermi liquid model, Valls and Tešanović arrived at an expression for the transition temperature for (p-type) superconductivity [12]:

$$T_c = 2T^* \exp(-1/\lambda) , \tag{1}$$

with T^* a characteristic temperature which can be identified either as the degeneracy temperature in the specific heat (UPt_3) or as a Kondo temperature ($CeCu_2Si_2$, UBe_{13}). With values for λ of $\frac{1}{3}$ and for T^* of the order of 10 K a value of T_c of the order of 1 K follows, not far from the experimentally observed value of 0.52 K for UPt_3. The same authors proposed to test eq. (1) in high pressure experiments, arguing that the pressure dependence of λ will be of minor influence. They expected an increase in the parameter T^* with pressure, due to an increase in the overlap between f orbitals and as a consequence an increase of T_c with pressure too.

Experiments, however, revealed a negative pressure dependence of T_c, whereas the positive pressure dependence of T^* was indeed observed [5].

Values for the characteristic temperature T^*, as derived from thermodynamic and transport prop-

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erties range between 6.5 K and 26 K for UPt_3. Some of these properties reveal large anisotropies even in their pressure dependence. Although anisotropies have been claimed to exist for the temperature dependence of the upper critical field [13], the zero-field value for the superconducting transition and its pressure derivative as measured by a resistive or ac susceptibility technique for vanishing current or in vanishing field are assumed to be independent of current or field direction with respect to the crystallographic axes.

In this contribution we present a detailed discussion of anisotropy effects in the pressure dependence of resisitivity and susceptibility as measured in high-pressure resistivity and in forced magnetostriction measurements. These latter results are compared with a direct observation of the pressure dependence of the susceptibility in high-pressure magnetization studies on a polycrystalline sample.

2. Experimental data

2.1. Resistivity under pressure

High-pressure resistivity data are shown in a plot of ρ versus T^2 in figs. 1a and b for current directions along the b- and c-axis, respectively. According to these results a description of ρ with a term quadratic in T only holds at the lowest temperature end. Writing $\rho = \rho_0 + \rho_T$ we observe ρ_0 to be pressure independent whereas the relative pressure effect of ρ_T increases at lower temperatures. Values for

$$\{\rho_T(4.2\,\text{kbar}) - \rho_T(1\,\text{bar})\}/\rho_T(1\,\text{bar})\}$$

measured along the a, b-axis range from −0.32 to −0.19 in the temperature interval 2.5–10 K and along the c-axis from −0.27 to −0.18. From the resistivity data of ref. [5], a value for $\{\rho_T(10.2\,\text{kbar}) - \rho_T(1\,\text{bar})\}/\rho_T(1\,\text{bar})$ of −0.32 can be derived along the c-axis between 0.5 K and 1.1 K. In this case a value for $(T^*)^{-1}\Delta T^*/\Delta p$ of 0.025 kbar^{-1} has been deduced, whereas in the present case, due to pronounced deviations from

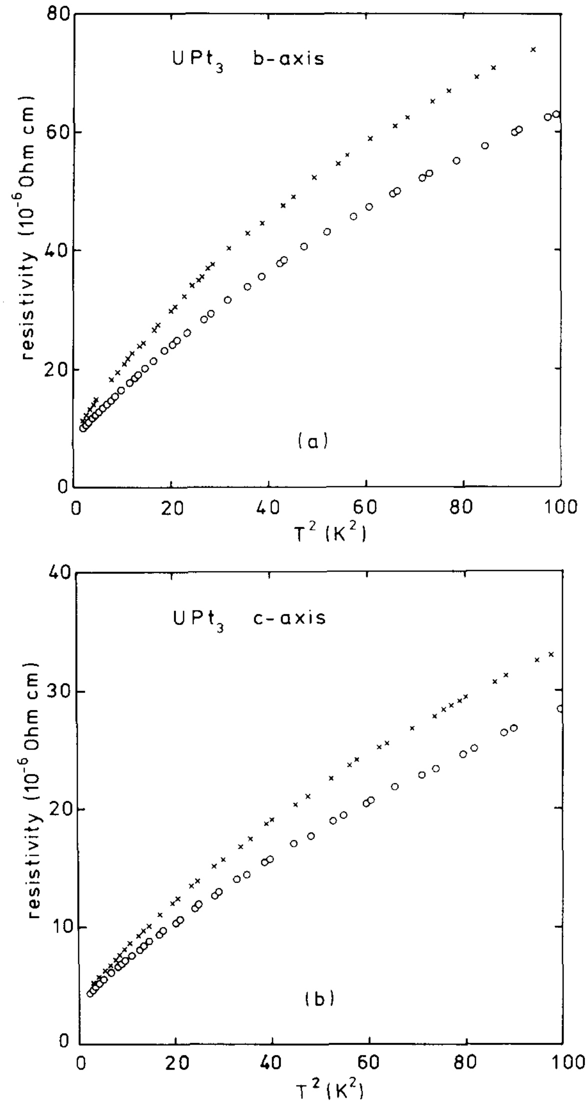

Fig. 1. Electrical resistivity versus T^2 for the compound UPt_3 at zero pressure (×) and at a pressure of 4.2 kbar (○) along the b-axis (a) and c-axis (b).

a T^2-dependence of the resistivity, no reliable value for the pressure dependence of T^* can be offered. The temperature derivative of the resistivity has a maximum at 6.5 K and 7.5 K for the a, b axes and c-axis, respectively. These temperatures increase under pressure at a rate of (0.35 ± 0.1) K/kbar. Assuming that this temperature is proportional to T^*, the corresponding value for $(T^*)^{-1}\Delta T^*/\Delta p$ is (0.05 ± 0.02) kbar^{-1} in the pressure interval from 1 bar to 4.2 kbar.

2.2 Susceptibility under pressure

High-pressure magnetization measurements have been performed on a cylindrical sample (diameter 6 mm, length 8 mm) with the external field parallel to the cylindrical axis. Due to preparation techniques, preferential orientations perpendicular to the cylindrical axis, occur for the c-axis. As a consequence, the susceptibility of this sample (104×10^{-9} m^3/mol at 4.2 K) is close to the value of 107×10^{-9} m^3/mol measured in the hexagonal plane of a monocrystalline sample at 4.2 K [14]. Experiments have been performed at 1 bar and 4.5 kbar in fields up to 8 T at temperatures below 30 K. The susceptibility decreases with increasing pressures resulting in a value for $\chi^{-1}\Delta\chi/\Delta p$ of -0.024 kbar^{-1}. In the susceptibility versus temperature curves a maximum is observed around 16 K for field directions in the hexagonal plane. Such a maximum is absent along the hexagonal axis. The temperature, T_m, at which this maximum is observed in our experiments on the polycrystalline sample, shifts from 17.6 K (1 bar) to 19.6 K (4.5 kbar). Taking this temperature to be proportional to the characteristic temperature T^* we deduce $(T^*)^{-1}\Delta T^*/\Delta p = 0.025$ kbar^{-1}. We note that the quantity $\chi(4.2\,\mathrm{K})T_m$ is almost pressure independent for this sample, a result that is easily understood in a paramagnon model for instance [5].

2.3. Forced magnetostriction

Forced magnetostriction data can be related to the hydrostatic pressure dependence of the molar magnetic moment by a thermodynamic Maxwell relation:

$$(\partial M/\partial p)_{H,T} = -(\partial V/\partial \mu_0 H)_{p,T} \tag{2}$$

or in terms of the relative pressure dependence of the molar susceptibility and molar volume by writing $M = \chi H$:

$$\frac{\chi}{\mu_0}\left(\frac{\partial \ln \lambda}{\partial p}\right)_{H,T} = -\frac{V}{\mu_0 H}\left(\frac{\partial \ln V}{\partial \mu_0 H}\right)_{p,T}.$$

In order to study the forced volume magnetostriction of this hexagonal compound, the relative length changes along the a, b and c directions were measured for each of the field directions along these three axes. Experimental results for $(\mu_0 H)^{-1}\partial \ln V/\partial \mu_0 H$ at $p = 1$ bar and $T = 4.2$ K in units of 10^{-7} T^2 are: 4.57, 4.66 and 0.31 for the external field along the a, b and c-axis, respectively [15].

Inserting these numbers in eq. (3), values for $\partial \ln \chi/\partial p$ of -0.023 kbar^{-1} and -0.003 kbar^{-1} have been calculated for field directions in the hexagonal plane and along the hexagonal axis, respectively. According to these results, pressure effects on the susceptibility of UPt_3 turn out to be largely anisotropic. High-pressure susceptibility experiments on a monocrystalline sample of UPt_3 are in progress in order to confirm this result.

3. Discussion

Due to a lack of theoretical understanding of the low-temperature anomalies that are observed in the physical properties of the heavy-fermion superconductor UPt_3, there is no proper definition for a characteristic temperature. Ad hoc definitions such as the temperature at which a maximum in $\chi(T)$, $\partial\chi/\partial T$, $\partial\rho/\rho T$ occurs, yield values for this temperature between 6.5 K and 16 K. Pressure effects on this temperature are positive. Taking the characteristic temperature T^* proportional to this temperature, we calculate values for $(T^*)^{-1}\Delta T^*/\Delta p$ between 0.025 and 0.050 kbar^{-1} from susceptibility and resistivity measurements in the pressure interval 1 bar to 4.5 kbar. The $\chi(T)$ and $\rho(T)$ curves measured on monocrystalline samples along different crystallographic axes show pronounced anisotropies. At the lowest temperature $\rho(T)$ is approximated by $\rho_0 + AT^2$ with values for A of 1.6 μΩ cm/K^2 and 0.7 μΩ cm/K^2 for current directions perpendicular and parallel to the hexagonal axis, respectively. With A proportional to $(T^*)^{-2}$ we obtain values for $(T^*)^{-1}\Delta T^*/\Delta p$ which fall inside the above given range of values for this parameter. The same conclusion holds for a value for $(T^*)^{-1}\Delta T^*/\Delta p$ derived from the pressure dependence of the susceptibility under the assumption that $\chi(T=0) = C/T^*$ with C an appropriate Curie constant. Forced volume magnetostriction measurements however, show that the pressure derivative of the susceptibility is strongly anisotropic. Low-temperature anomalies in the susceptibility along the c-axis are hardly detectable and values for $\partial \ln \chi/\partial p$ along this axis are one order of magnitude smaller than the corresponding values along the a and b axes. Anomalies connected with the large effective mass of the electrons at low temperatures are apparently absent in the susceptibility along the hexagonal axis.

When comparing the high-pressure susceptibility data with the forced volume magnetostriction results we have to keep in mind that volume changes in the magnetostriction measurements in fields up to 3 T are at least two orders of magnitude smaller than the volume changes induced by a pressure of 4 kbar (the compressibility of UPt_3 at room temperature equals 0.48 Mbar^{-1}). Nevertheless, when evaluating values for $\partial \ln \chi_{a,b}/\partial p$ from forced magnetostriction and high-pressure magnetization studies we arrive at nearly identical results, indicating a linear pressure dependence of $\chi_{a,b}$ at least up to 4.5 kbar.

4. Conclusions

Although no clear-cut definition of the characteristic temperature for the low temperature anomalies in resistivity and susceptibility can be presented, we have shown that values for the relative pressure dependence of T^*, as determined from the pressure induced shift in the maxima of $\chi(T)$ and $\partial \rho/\partial T$ are between 0.025 and 0.050 kbar^{-1}. Values for this parameter derived from a more sophisticated analysis such as the pressure dependence of the coefficient A of the term in ρ quadratic in temperature (0.025 kbar^{-1}, [5]), the combination of specific heat and thermal expansion (0.031 kbar^{-1}, [16]), the forced magnetostriction and the pressure dependence of the susceptibility at 4.2 K (0.024 kbar^{-1}), all satisfactorily agree with the directly observed pressure induced shift in T^*. The positive value for $\partial \ln T^*/\partial p$ is firmly established by these different experimental methods and clearly deviates from a value of $-0.026\ \mathrm{kbar}^{-1}$ for $\partial \ln T_c/\partial p$ [5].

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