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High-pressure resistance study of UTe

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Abstract. Low-temperature resistance measurements were performed on UTe crystals in the pressure range from 1 GPa to 20 GPa. The Curie temperature, obtained as the maximum in the temperature derivative dR/dT, increases strongly with pressure. It has a maximum at 7.5 GPa followed by a decrease with a smaller slope at higher pressures. Another anomaly in the R–T characteristic is observed above 10 GPa and ascribed to the presence of the B2 phase, which is known to form in a very sluggish phase transformation.

1. Introduction

Although a great deal of experimental work has been done on UTe, there is as yet no final interpretation of its electronic behaviour. Resistivity measurements by Schoenes *et al* [1] show a $T^2\exp(-d/kT)$ behaviour in the temperature range from 4 K up to 70 K. They found the ferromagnetic ordering as a maximum in the derivative dR/dT at 102 K. With increasing temperature the resistivity has a maximum, followed by a decrease with a minimum at 800 K [2]. This region of the resistivity curve fits well to a Kondo formalism. Magnetization measurements yield a Curie temperature of 104 K and show a large anisotropy in the magnetic moment [3]. Low-temperature x-ray diffraction shows a distortion of the cubic lattice below the ordering temperature [4].

High-pressure x-ray diffraction studies on UTe powder by Léger *et al* [5] revealed that its bulk modulus (45 GPa for the B1 phase) is considerably lower than those of USe and US. The transition from the B1 to the B2 phase started at 11 GPa and was completed at 19 GPa. Gerward *et al* obtained nearly the same results [6]. Both groups report a strong hysteresis: upon releasing the pressure, UTe remains in the B2 phase even down to ambient pressure.

Recent theoretical work by Cooper *et al* has led to the conclusion that UTe is almost an itinerant ferromagnet like iron [7]. To provide an additional piece in the puzzle we have performed high-pressure resistance measurements on UTe.

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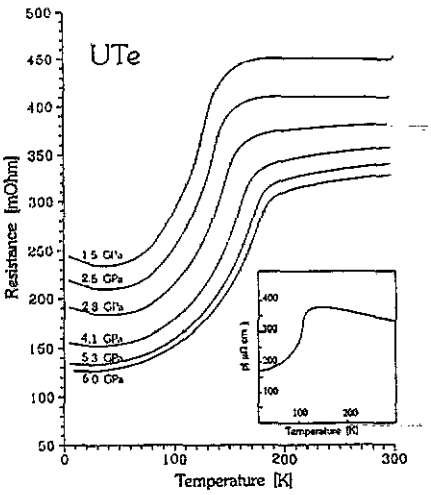

Figure 1. Resistance of UTe at pressures from 1.5 GPa to 6.0 GPa. Inset shows ambient pressure resistivity from Schoenes *et al* [1] for comparison.

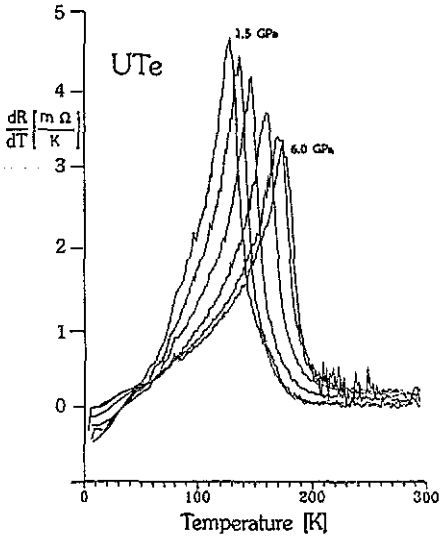

Figure 2. dR/dT of UTe at pressures from 1.5 GPa to 6.0 GPa.

2. Experimental details

The measurements described here were performed in a liquid-helium bath cryostat. By pumping on the bath, temperatures down to 1.5 K were accessible. The press used is of the opposed anvil type. The anvils are made of sintered diamond with a flat surface of 2 mm diameter and allow pressures of more than 20 GPa to be attained. The press and the high-pressure cell have already been described elsewhere [8, 9]. The temperature was measured with a Pt100 platinum resistor between 300 K and 50 K and with a calibrated Ge resistor below 50 K. The pressure was determined from the superconducting transition temperature of a small Pb foil placed next to the sample, using the calibration table of Bireckoven and Wittig [10]. The sample resistance, as well as the Pb resistance, were measured by a four-probe DC method. The samples used were flat plates cleaved perpendicular to the [100] axis from a UTe single crystal.

3. Results

At zero pressure the resistance of our UTe crystals shows qualitatively the same behaviour as described by Schoenes *et al* [1]. For low pressures we observe a small increase in the resistance at low temperatures, which was not reported by Schoenes *et al*. In the pressure range up to 7.5 GPa the resistance of UTe decreases with increasing pressure at all temperatures (figure 1). We also observed a remarkable increase in the Curie temperature (derived from the maximum of dR/dT) with increasing pressure (figure 2). The Curie temperature increases from 112 K at 0.32 GPa to a maximum of 181 K at 7.5 GPa, i.e. $d\ln T_c/dp = 66\ \mathrm{TPa}^{-1}$. The extrapolated value of T_c for zero pressure amounts to 110 K, slightly higher than the values of 102 K [1] and 104 K [3] reported in the literature, and the initial slope of 13 K GPa^{-1} is in good agreement with the 14 K GPa^{-1}

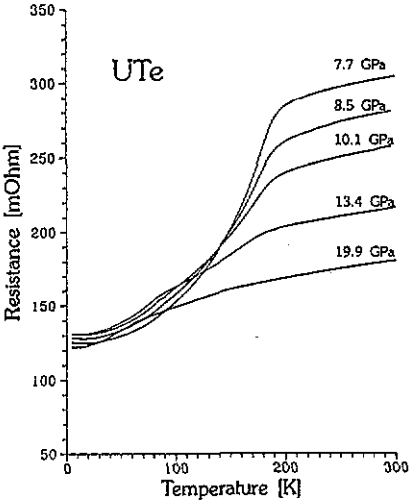

Figure 3. Resistance of UTe at pressures from 7.7 GPa to 19.9 GPa.

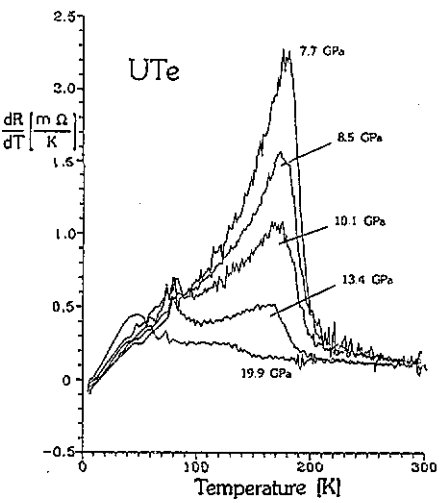

Figure 4. dR/dT of UTe at pressures from 7.7 GPa to 19.9 GPa.

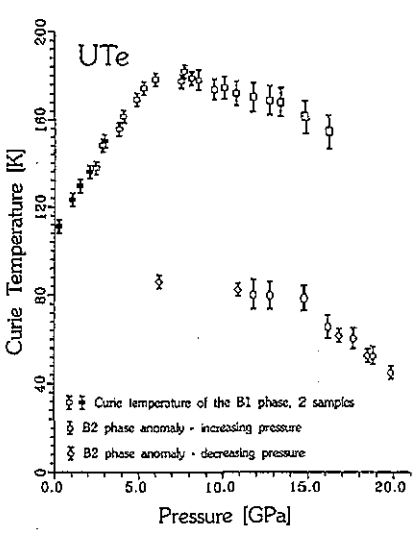

Figure 5. Curie temperature of the B1 phase and the temperature of the B2 phase anomaly of UTe.

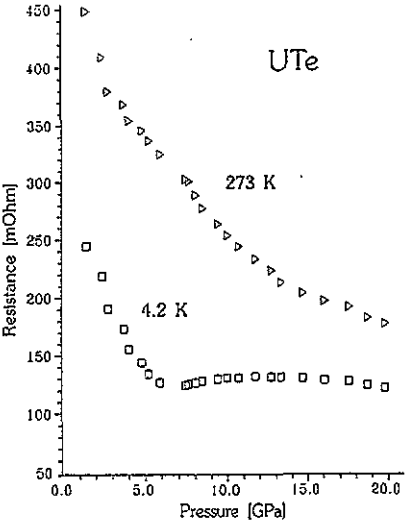

Figure 6. Pressure dependence of the resistance of UTe at 273 K and 4.2 K.

reported by Bartholin *et al* [11]. Above 7.5 GPa the Curie temperature decreases slightly with increasing pressure, and above 10 GPa a second maximum at 80 K builds up in the derivative, while the maximum associated with the Curie temperature of the B1 phase successively disappears (figures 3 and 4).

Figure 5 shows the pressure dependence of the Curie temperature of the B1 phase of two independent samples of UTe in the whole pressure range. The error bars indicate an estimate of the uncertainty in the maximum of dR/dT. Above 10 GPa we observed a new anomaly at about 80 K (figures 3 and 4). This anomaly, which we interpret as a

feature of the B2 phase, becomes more pronounced with increasing pressure. Upon releasing the pressure the anomaly remained visible down to 5 GPa (the lowest pressure reached before the cell failed), while the anomaly due to the B1 phase Curie temperature did not reappear.

The resistance at 4.2 K decreases rapidly up to 7.5 GPa (figure 6). It increases slightly between 7.5 GPa and 10 GPa and remains almost constant above 10 GPa, while the resistance at 273 K decreases with pressure over the whole pressure range. This change of the 4.2 K resistance behaviour at 7.5 GPa may signal the gradual appearance of the B2 high-pressure phase. Nevertheless we believe that the B2 phase is not present in the sample in an appreciable amount below 10 GPa.

4. Discussion

For the discussion of our results, we have added to figure 1 the zero pressure resistivity of UTe, as published by Schoenes *et al* [1]. It is seen that the resistivity has a maximum above the Curie temperature. With increasing temperature the resistivity decreases to a *minimum* around 800 K [2]. This has led to the notion that UTe is a dense Kondo system which nonetheless orders ferromagnetically. Our results show that the negative temperature coefficient of the resistance above 200 K changes into a positive one with increasing pressure. This indicates that applying pressure suppresses the Kondo behaviour. One possible interpretation of the rise of the Curie temperature in UTe is based on a coexistence of ferromagnetic inter-atomic exchange and antiferromagnetic intra-atomic Kondo coupling. Suppressing the Kondo coupling should then lead to the increase in the Curie temperature. Such an interplay of ferromagnetic exchange and Kondo coupling was also investigated in $U_{1-x}La_xTe$ compounds [12], where the Curie temperature decreases with increasing La concentration and the Kondo regime can thus be observed to lower temperatures.

Our discussion of the magnetic behaviour of UTe so far is based mainly on the increase in the delocalization of the 5f states under pressure. This increasing overlap of wavefunctions may also explain the generally observed decrease of the resistance with pressure up to 7.5 GPa.

The slight decrease of the Curie temperature above 7.5 GPa can be explained within an itinerant electron picture, as found for uranium sulphide: magnetization measurements on uranium sulphide show a small decrease ($d\ln T_c/dp = -12.6\,TPa^{-1}$) of the Curie temperature (180 K at ambient pressure) with increasing pressure, in accordance with the assumption of iron-like itinerant magnetism [13, 14].

Another feature in the family of curves in figure 1 is worth mentioning. There is a distinct increase in the resistance on cooling below about 30 K, reminiscent of an ordinary Kondo minimum. With increasing pressure the minimum gradually becomes shallower and, eventually, is entirely absent at pressures above 7.5 GPa. This resistance minimum is somewhat reminiscent of the low-temperature resistance anomaly found in dilute Th–U alloys [15], which is ascribed to the formation of a non-magnetic ground state of the U 'impurity' by an antiferromagnetic spin compensation. In the present case, by analogy we may tentatively attribute the resistance minimum to single U 'impurity' atoms in a slightly off-stoichiometric UTe matrix with some Te deficiency. Although our interpretation of an antiferromagnetic interaction between single 5f moments and the band charge is rather speculative for a hypothetical U impurity in a ferromagnetically

ordered UTe matrix, it is consistent with the picture that in UTe the antiferromagnetic exchange interaction is increasingly weakened at higher pressure.

The second resistance anomaly around 80 K appears at a pressure not far above the region of transition from correlated to itinerant behaviour, and shows hysteresis upon releasing the pressure. As known from high-pressure x-ray diffraction, the crystallographic phase transition from the B1 to the B2 phase is found to be very sluggish. It extends over the pressure range from 10 GPa to 20 GPa, and the B2 phase is stable upon releasing the pressure [5, 6]. On these grounds we conclude that the new resistance anomaly appearing around 80 K is related to the B2 phase.

5. Conclusion

Resistance measurements on UTe under pressure reveal two different effects. Firstly, there is a strong increase in the Curie temperature up to a maximum, followed by a slight decrease. This variation in the Curie temperature can be interpreted as a transition from localized ferromagnetic to itinerant electron behaviour.

Secondly, another resistance anomaly is observed above 10 GPa, most clearly shown by a maximum in dR/dT at about 80 K. The fact that it develops in the pressure range of the B1 to B2 transition and that it is stable upon releasing the pressure indicates that it is a characteristic feature of the B2-type phase.

Magnetization measurements of UTe under high pressure will be useful to obtain direct confirmation of the variation of magnetic properties deduced from the present study of the electrical resistance under pressure.

Acknowledgments

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