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The pressure effect on magnetism in $CeTe_{1.82}$

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Abstract

We report the pressure effect of the normal-state transport and magnetic properties of $CeTe_{1.82}$ up to 9 kbar. We found that the applied pressure increases the Kondo temperature ($T_K^* \sim 170$ K), which is associated with the two-dimensional motion of carriers confined within the Te plane. Both the short-range ferromagnetic ordering temperature ($T_{SRF} \sim 6$ K) and the long-range antiferromagnetic transition temperature ($T_N \sim 4.3$ K) are slightly increased with pressure. We suggest that the application of pressure enhances coupling between the 4f and conduction electrons. While applying the magnetic field, a large magnetoresistance is observed in the vicinity of T_{SRF}, which is analogous to that at ambient pressure.

1. Introduction

The generally accepted picture in f-electron systems is that the f electrons are responsible for the local magnetic moments and are strongly correlated with itinerant conduction electrons [1]. Then, two magnetic interactions are expected. One is the on-site Kondo interaction, a screening of the local magnetic moment by conduction electrons, which develops a nonmagnetic ground state. The other is the indirect RKKY exchange interaction between the localized f magnetic moments mediated by the conduction electrons, favoring long-range magnetic ordering. Consequently, the balance between these two competing interactions leads to various ground states [2].

A striking feature in f-electron systems is that for certain rare-earth compounds the magnetic order on the rare-earth sublattice has been found to coexist with a superconducting state [3]. Recently, we have reported the coexistence of magnetism and a charge density wave along with superconductivity in $CeTe_{1.82}$ [4]. Here the magnetic moments are not significantly changed at the superconducting transition and the Te vacancies involving the charge-density-wave modulation play an important role in forming the pairing of the superconductivity [4]. In this paper, we report the normal-state properties of $CeTe_{1.82}$ as functions of pressure and magnetic field. At ambient pressure, this compound displays two different magnetic orderings. The local magnetic moments of Ce ions develop a short-range ferromagnetic ordering in the CeTe layer below $T_{SRF} \sim 6$ K which is of magnetoelastic origin. The short-range ferromagnetic CeTe layers change to having long-range ferromagnetic order in the layers and simultaneously long-range antiferromagnetic order in the spin sequence of down-up–up-down along the c axis below $T_N \sim 4.3$ K [5]. Finally, there appears to be superconductivity below $T_c \sim 2.7$ K at pressures higher than 2 kbar [4].

2. Experimental method

Samples of $CeTe_{2-\delta}$ were prepared by the mineralization method, as described previously [5]. By cleaving the ingot of $CeTe_{2-\delta}$, a few pieces of plate-like single crystals of size $1 \times 1 \times 0.5$ mm^3 with (001) surfaces were taken for high-pressure experiments. Powder x-ray-diffraction patterns indicated that the samples are almost single phased with tetragonal Cu_2Sb-type structure with the lattice parameters $a = 4.47$ Å and $c = 9.11$ Å, in good agreement with those reported previously [5]. Electron-probe microanalysis showed that the compositions are deficient in Te content, i.e. $CeTe_{1.82}$, even though the starting composition was 5% in Te content. For high-pressure experiments, we used high-purity BeCu alloy for the piston–cylinder type pressure cell. The pressure was determined to ±0.005 kbar from the electrical resistance of a Manganin sensor. Mineral oil was used as the pressure transmitting medium.

3. Results and discussion

Figure 1 shows the results of electrical resistivity $\rho(T)$ for $CeTe_{1.82}$ with three different current directions, applied in the

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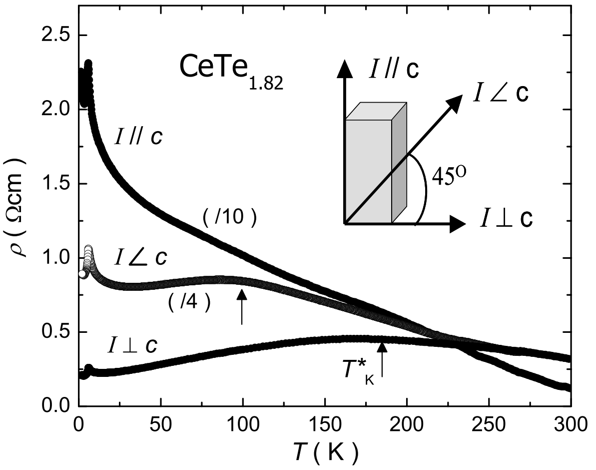

Figure 1. Electrical resistivity $\rho(T)$ with different current directions applied in the *ab* plane ($I \perp c$), along the direction of 45° in the plane ($I\angle c$), and along the *c* axis ($I \parallel c$). For clarity, the resistivity values have been scaled by a factor of 4 for $I\angle c$ and 10 for $I \parallel c$. The arrows indicate the coherent Kondo temperature, T_K^*.

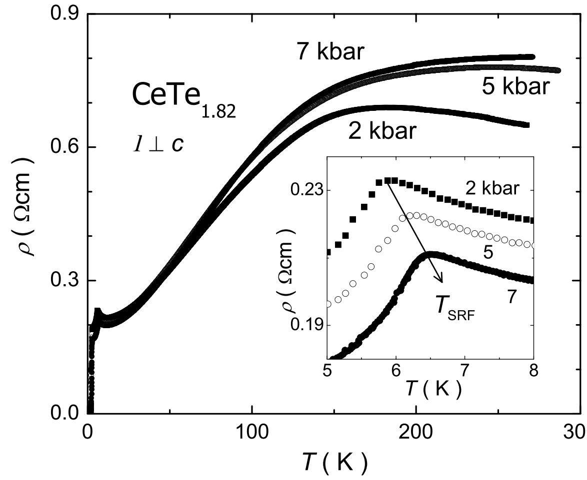

Figure 2. In-plane resistivity $\rho_{\perp c}(T)$ measured at several pressures, 2, 5, and 7 kbar. The inset shows the low-temperature data, clarifying the short-range ferromagnetic ordering temperature, T_{SRF}.

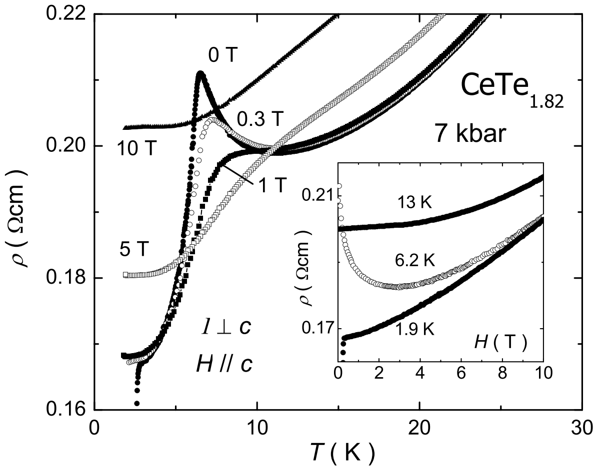

Figure 3. In-plane resistivity $\rho_{\perp c}(T)$ for the various *c*-axis magnetic fields, 0, 0.3, 1, 5, and 10 T. The inset shows the magnetoresistance (MR) measured at different temperatures, 1.9, 6.2, and 13 K.

basal plane of the tetragonal unit cell ($I \perp c$), along the direction of 45° in the plane ($I\angle c$), and along the *c* axis ($I \parallel c$). For clarity, the resistivity values have been scaled by a factor of 4 for $I\angle c$ and 10 for $I \parallel c$. The absolute values are of the order of $\rho_{\perp c} < \rho_{\angle c} < \rho_{\parallel c}$. Metallic behavior is shown for $\rho_{\perp c}$ and semiconducting behavior appears for $\rho_{\parallel c}$, reflecting the anisotropic behaviors. A broad maximum at $T_K^* \sim 170$ K in $\rho_{\perp c}$ is associated with the onset of the Kondo-lattice ground states, as observed in other Ce-based intermetallics [1]. This maximum moves to a lower temperature (100 K) for $\rho_{\angle c}$ and finally disappears for $\rho_{\parallel c}$.

This result is well understood in terms of the anisotropic Kondo effect because the Kondo temperature is exponentially proportional to the density of states at the Fermi level. Thus, the Kondo temperature is lower with changing current direction from the metallic *ab* plane to the semiconducting *c* axis. The *c*-axis semiconducting state cannot be mapped by the Kondo picture because the Kondo effect requires a moderate carrier density. On the other hand, a sharp peak at $T_{\mathrm{SRF}} \sim 6$ K, not at $T_N \sim 4.3$ K, is suggested as a result of short-range ferromagnetic order by magnetic polarons [5]. Since the magnetic polarons are coupled with carrier localization and spin polarization, it is natural that this effect is most dominant at temperatures just above T_N and is independent of the current direction. If this is indeed the cases, it is natural to expect that the two features, short-range ferromagnetic order and antiferromagnetic Néel order, should be drastically affected by external parameters such as applied pressure and magnetic field.

The pressure variations of $\rho_{\perp c}(T)$ are illustrated in figure 2 for the whole temperature region and in the inset for the low-temperature region. There are three remarkable pressure effects in $\mathrm{CeTe}_{1.82}$. First, the resistivity curves cross at a temperature between T_K^* and T_{SRF}, because the high-temperature resistivity increases but the low-temperature resistivity decreases while applying the pressure. This may be due to the different crystalline-electric-field effects caused by contraction of an anisotropic lattice under pressure. Second, the applied pressure changes the position of the Kondo feature at T_K^* to a higher temperature. This result is easily explained since the Kondo interaction is enhanced as a result of the increased Kondo coupling constant by an applied pressure. Third, the low-temperature magnetic feature at T_{SRF} moves slowly to higher temperature with increasing pressure. This result gives evidence that the number of magnetic polaron states is increased upon shrinking the crystal lattice.

The existence of magnetic polaron states can be investigated by measuring the magnetic field dependence of $\rho_{\perp c}(T)$ under pressure. In figure 3, the sharp peak at T_{SRF} is strongly suppressed and shifts to higher temperatures with increasing magnetic field which is similar to the result at ambient pressure [5]. This also leads to a large negative magnetoresistance (MR) in the vicinity of T_{SRF}. As shown in the inset of figure 3, MR measured at temperatures below (1.9 K) and above T_{SRF} (13 K) increases monotonically, while

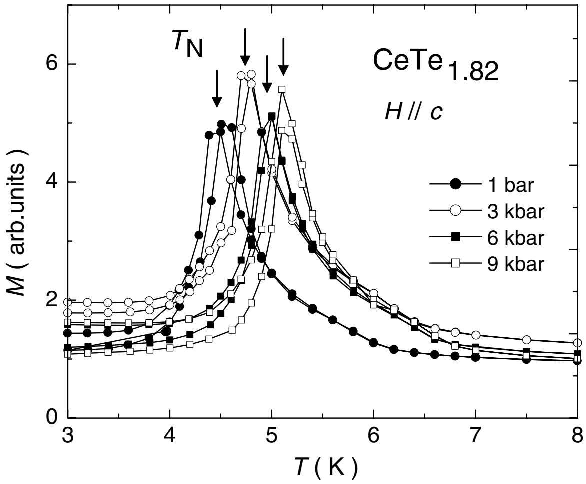

Figure 4. Magnetization measured in a field of 50 Oe at various pressures: 1 bar, 3, 6, and 9 kbar. The arrows indicate the long-range antiferromagnetic transition temperature, T_N.

MR at around T_{SRF} (6.2 K) initially decreases with increasing fields but then increases which gives a broad minimum at 3 T. This negative MR behavior at low fields is a characteristic of the low-carrier-density materials with magnetic polaron states.

In order to investigate the pressure effect on the antiferromagnetic order at T_N, we have measured the magnetization $M(T)$ in a field of 50 Oe while varying pressure, which is shown in figure 4. There is a small difference between zero-field-cooled (ZFC) and field-cooled (FC) data at around T_{SRF}, which is due to the short-range ferromagnetic ordering. A sharp peak associated with the long-range antiferromagnetic order at T_N increases almost linearly with increasing pressure at a rather large rate of $dT_N/dP = 0.06$ K kbar^{-1}. This implies strong hybridization between the localized 4f electrons and the conduction electrons due to the decrease in interatomic distance by the applied pressure. This strong magnetic interaction can cause the itinerant conduction electrons to be superconducting, as reported previously [4]. Surprisingly, no superconductivity was found in other single crystals of CeTe$_{1.85}$ and CeTe$_{1.87}$, which implies that superconductivity is found only in the narrow region of Te composition.

Special attention should be given to the quantum critical point (QCP) in CeTe$_{1.82}$ obtained upon applying pressure. As expected from the Doniach phase diagram [2], the QCP is normally connected to nearly heavy-fermion metals on the border of antiferromagnetic and ferromagnetic states (Néel or Curie temperature, T_N or $T_C \to 0$ K) [6]. In this case, at the phase boundary, instead of Fermi-liquid behavior, non-Fermi-liquid (NFL) behavior may appear [7]. In CeTe$_{1.82}$, instead, the superconducting transition is observed at $T_c = 2.7$ K well below the magnetic ordering temperatures (T_{SRF} and T_N), and the normal-state properties are also far from the NFL behavior. Combining these observations and the narrow composition of Te for the superconductivity, we suggest that this pressure-induced superconductivity is mediated by phonons, possibly enhanced by the ferromagnetic fluctuations inside the magnetic ordering phase [4].

4. Conclusions

In conclusion, for the CeTe$_{1.82}$ single crystals, we confirmed the crossover from metallic behavior in the ab plane to semiconducting behavior along the c axis. Also this compound displays various collective ground states; Kondo-lattice coherence ($T_K^* \sim 170$ K) in the metallic ab plane, short-range ferromagnetic ordering (at $T_{SRF} \sim 6$ K) in the plane, long-range antiferromagnetic transition ($T_N \sim 4.3$ K) along the c axis, and finally superconducting transition ($T_c \sim 2.7$ K) under pressure. We found that the Kondo interaction T_K^* is enhanced by an applied pressure. The pressure effect on both short-range ferromagnetism and antiferromagnetism was investigated. We also conclude that the pressure is required to enhance the magnetic exchange interaction and superconducting state.

Acknowledgments

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