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Magnetic order of rare-earth tritelluride CeTe$_3$
at low temperature

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Abstract. Rare-earth tritelluride CeTe$_3$, which belongs to the family of quasi-two-dimensional compounds RTe$_3$ (where R = Y, La-Sm, Gd-Tm), has highly two-dimensional crystal structure. Fermi surfaces consist of inner and outer square sheets, large regions of which are nested by a single incommensurate wave-vector. Because of the characteristic quasi-two-dimensional nature of square Fermi surfaces, the charge density wave of RTe$_3$ is formed with an extremely large gap and extensively investigated. Despite the extensive studies on the charge density wave in recent years, remarkably little is known about magnetism and low-temperature properties of CeTe$_3$. We have investigated the low-temperature magnetic-ordered-phases of the rare-earth tritelluride CeTe$_3$ with single crystals. We measured specific heat, electrical resistivity and differential magnetic susceptibility using a $^3$He cryostat down to about 0.45 K and a $^3$He/$^4$He dilution refrigerator down to 0.1 K. We have found that heavy quasi-particles form spin density wave at low temperatures, reflecting the square Fermi surfaces with the quasi-one-dimensional nature.

1. Introduction
Rare-earth tritelluride CeTe$_3$, which belongs to the family of quasi-two-dimensional compounds RTe$_3$ (where R = Y, La-Sm, Gd-Tm), has highly two-dimensional crystal structure (Fig. 1); RTe-slabs and two square Te-sheets are stacked along the b-axis (space group Cmcm, weakly orthorhombic structure) [1, 2]. RTe-slabs contribute to magnetism [1, 3] and square Te-sheets form two-dimensional conducting bands, which give strongly anisotropic transport properties [2]. First-principles band-structure calculations reveal that the Fermi surface consists of inner and outer square sheets, large regions of which are nested by a single incommensurate wave-vector corresponding to the observed lattice-modulation [4, 5]. Because of the characteristic quasi-two-dimensional nature of the Te sheet, the charge density wave (CDW) is formed with an extremely large gap of the order of 100 meV [6–9]. Despite the extensive studies on the CDW in recent years [10–13], remarkably little is known about magnetic properties of CeTe$_3$ at low temperatures. Here we report the experimental results of electrical resistivity, differential magnetic susceptibility and heat capacity at low temperatures with single crystals of CeTe$_3$. 

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2. Experimental

Single crystals were grown by a self-flux technique. Elements in the molar ratio Ce:Te = 1:40, were put into alumina crucibles and vacuum sealed in quartz tubes. The mixtures were heated to 850 °C and slowly cooled over a period of 4 days to end temperatures in the range of 500 °C. The in-plane electrical resistivity was measured by a conventional four-probe method using gold wires lead and gold paste. The differential susceptibility was measured using a drive field $H_{ac} \sim 1$ Oe and counter-wound pickup coils. For experiments, an excitation frequency of 83 Hz was employed. Temperature was cooled down to 0.1 K using a $^3$He/$^4$He dilution refrigerator. The specific heat measurements were carried out by an adiabatic heat-pulse method in a $^3$He cryostat down to about 0.45 K.

3. Results and Discussion

Figure 2(a) shows the temperature dependence of the specific heat divided by temperature. We observe a broad rounded peak at $T_{N1} = 3.1$ K (corresponding to the Neel temperature reported previously [1, 2]) and a sharp specific-heat jump at $T_{N2} = 1.3$ K. The broad feature of the peak at

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**Figure 1.** Schematic diagram showing the crystal structure of CeTe$_3$. Black lines show the unit cell with lattice parameters $a \approx c \sim 4$ Å and $b \sim 26$ Å. Red and blue circles denote the Ce and Te atoms, respectively.

**Figure 2.** Temperature dependence of the specific heat divided by temperature, the electrical resistivity and the differential magnetic susceptibility of CeTe$_3$. Arrows denote the anomalies associated with two magnetic transitions at $T_{N1} = 3.1$ K and $T_{N2} = 1.3$ K.
Figure 3. The real part of the differential magnetic susceptibility through the magnetic transitions in CeTe$_3$ for $H \parallel c$-axis at several temperatures. Arrows denote the anomalies associated with two magnetic transitions at $H_{c1}(T)$ and $H_{c2}(T)$.

$T_{N1}$ is possibly related to the low-dimensional character of CeTe$_3$. On the contrary, the specific heat jump at $T_{N2}$ indicates a molecular-field like transition. The double phase transitions are also seen in the electrical resistivity for the current flowing along the $a$-axis in Fig. 2(b). There is a sharp drop in the resistivity associated with the loss of spin-disorder scattering below $T_{N1}$ and a small anomaly like a hump just below $T_{N2}$. Figure 2(c) shows the temperature dependence of the differential magnetic susceptibility for $H_{ac} \parallel c$-axis and $H_{ac} \parallel b$-axis. The real part of the susceptibility shows a small kink at $T_{N1}$ for both directions, which corresponds to the magnetic transition from paramagnetic phase in previous reports. Since the anomaly is very small, the magnetic transition is supposed to be not a simple antiferromagnetic transition. Below $T_{N2}$ the magnetic susceptibility for $H_{ac} \parallel c$-axis decreases steeply, while little anomaly is found for $H_{ac} \parallel b$-axis. Therefore, the anomaly at $T_{N2}$ indicate the phase transition from the intermediate phase to an additional antiferromagnetic phase with an in-plane easy axis.

Figure 3 shows magnetic field dependence of the real part of the differential susceptibility for $H \parallel c$-axis at several temperatures. The data of $T = 0.2$ K contains a main peak at approximately 1.6 T and a much weaker anomaly at approximately 3.7 T. The main peak shifts to lower field and washes out at $T_{N2}$ as the temperature is increased. The weak anomaly also shifts and merges at $T_{N1}$. We define the anomalies associated with two magnetic transitions as the critical magnetic fields $H_{c1}(T)$ and $H_{c2}(T)$, which correspond to the two magnetic-ordered-phases for $T_{N1}$ and $T_{N2}$, respectively. $H - T$ phase diagram of CeTe$_3$ for $H \parallel c$-axis, deduced from the differential susceptibility, is shown in Fig. 4. The anomaly at $H_{c1}(T)$ indicates that the...
magnetization is almost saturated by magnetic field and that the second order phase transition to paramagnetic phase occurs [1]. In contrast to the anomaly of $H_{c1}(T)$, the shape peak at $H_{c2}(T)$, where the magnetic field destroys the ordered phase at lower temperature, develops steeply and might diverge at zero temperature. This behavior implies the phase transition at $H_{c2}(0)$ involves the drastic change of the ground state.

The specific heat measurement shown in Fig. 2(a) indicates the rare-earth tritelluride CeTe$_3$ forms heavy quasi-particles at low temperatures; $\gamma(T) = C(T)/T$ amounts to 0.4 J/mole K$^2$ at 4 K. In the intermediate phase, $\gamma(T) = 0.9$ J/mole K$^2$ at 0.5 K $< T_{N2}$ recovers with entropy balance by application of magnetic field $\mu_0 H = 1.6$ T $> \mu_0 H_{c2}$. Furthermore, the incommensurate magnetic Bragg peak develops below $T_{N2}$ in zero fields [14]. These results confirm that the system condenses into an incommensurate spin density wave (SDW) state of heavy quasi-particles below $T_{N2}$. Thus we have concluded that the magnetic order of CeTe$_3$ at low temperatures develops from the paramagnetic phase to the SDW phase through the intermediate phase with the formation of heavy quasi-particles with decreasing temperature, though the intermediate phase $T_{N2} < T < T_{N1}$ is still unclear.

4. Summary
We have investigated the low-temperature ordered phases of the rare-earth tritelluride CeTe$_3$ with single crystals. The specific heat, the electrical resistivity and the differential magnetic susceptibility measurements of CeTe$_3$ indicate that the magnetic order of CeTe$_3$ develops from the paramagnetic phase to the SDW phase through the intermediate phase with the formation of heavy quasi-particles. These results suggest that the magnetic order of Ce local moments at low temperatures closely relates with the characteristic quasi-two-dimensional nature of the square Fermi surfaces.

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