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LETTER TO THE EDITOR

An anomalously huge resistivity peak under pressure in CeRhGe

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Abstract
We have measured the electrical resistivity under pressure up to 2 GPa for an antiferromagnet, CeRhGe. The resistivity at ambient pressure decreases monotonically below a Néel temperature $T_N = 10$ K. With increasing pressure P, the resistivity has a peak around 10 K, which is anomalously enhanced up to 1.2 GPa. With further increasing pressure, the resistivity peak is diminished; the Néel temperature becomes zero at a critical pressure $P_c = 1.9$ GPa. The A-value of the resistivity ρ in the Fermi liquid relation $\rho = \rho_0 + AT^2$ is also found to increase with increasing pressure and has a maximum at P_c which corresponds to the value for the heavy-fermion superconductor $CeCu_2Si_2$.

Cerium and uranium compounds exhibit a variety of phenomena such as magnetic, quadrupole and charge orderings, heavy fermions, Kondo insulators and unconventional superconductivity [1]. The recent experiments on these compounds have been carried out under pressure. With increasing pressure, the magnetically ordered state can be changed into a paramagnetic state—the so-called heavy-fermion state—passing through a non-Fermi liquid state and/or a superconducting state. $CeIn_3$, $CeRhIn_5$ and UGe_2 are typical compounds showing pressure-induced superconductivity [2–4]. It is surprising that the ferromagnet URhGe, which has a Curie temperature $T_C = 9.5$ K and a saturation moment 0.42 μ_B/U, was reported to become a superconductor below 0.25 K at ambient pressure [5].

In order to gain a deeper understanding of the interplay between the magnetism and superconductivity, we have carried out research on a new compound—namely a resistivity measurement under pressure. In the present letter we have investigated the electrical properties

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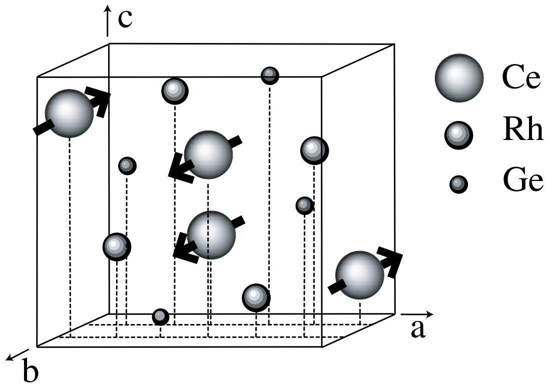

Figure 1. Crystal and magnetic structures of the antiferromagnet CeRhGe.

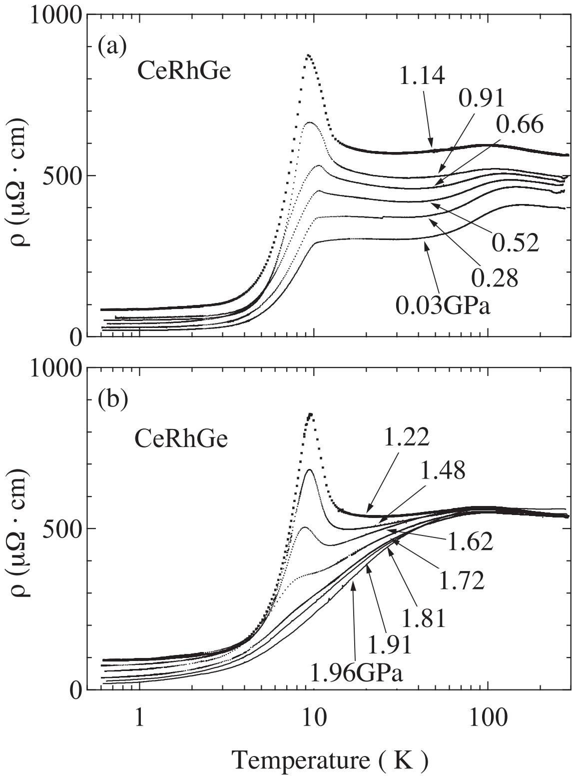

Figure 2. The temperature dependence, on a logarithmic scale, of the electrical resistivity under pressure in CeRhGe.

of CeRhGe under pressure and have found a new magnetic state with an anomalously huge resistivity peak.

CeRhGe crystallizes in the TiNiSi-type orthorhombic structure (space group *Pnma*) with the lattice parameters $a = 7.433$ Å, $b = 4.454$ Å and $c = 7.041$ Å at 1.7 K [6], as shown in figure 1. The crystal structure of CeRhGe is the same as that of URhGe mentioned

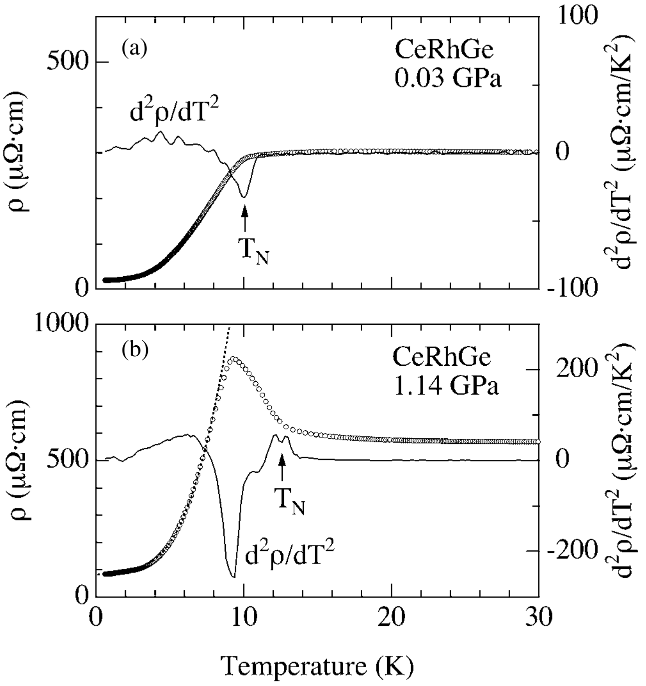

Figure 3. The temperature dependence of the resistivity ρ and the resistivity in the form $d^2\rho/dT^2$ under (a) 0.03 GPa and (b) 1.14 GPa in CeRhGe; the Néel temperature T_N is indicated by arrows. A dotted curve in (b) shows the theoretical curve described in the text.

above. The magnetic susceptibility follows the Curie–Weiss law with an effective moment $\mu_{\mathrm{eff}} = 2.3\ \mu_B/\mathrm{Ce}$, close to that, $2.54\ \mu_B/\mathrm{Ce}$, for a free Ce^{3+} ion. This compound orders antiferromagnetically below $T_N = 10$ K. The magnetic moment is directed along the b-axis, with an ordered moment of $0.9\ \mu_B/\mathrm{Ce}$ [6], as shown in figure 1. The electronic specific heat coefficient is obtained as 75 mJ K^{-2} mol^{-1}, indicating a relatively large value [7]. CeRhGe is thus characterized as a Kondo compound with magnetic ordering.

Polycrystal samples were synthesized by arc melting under an argon atmosphere using 99.9% (3N) pure Ce, 4N Rh and 5N Ge in the stoichiometric proportions 1:1:1 and were annealed at 800 °C for one week. The pressure experiment was carried out by making dc-resistivity measurements using a MP35N piston–cylinder cell. The pressure-transmitting medium was a commercial Daphne oil (7373). The pressure was determined from the superconducting transition temperature of Sn.

Figure 2 shows the temperature dependence, on a logarithmic scale, of the electrical resistivity under pressure up to 2 GPa. The resistivity at 0.03 GPa has two broad peaks at 130 and 15 K. This is typical of a Kondo compound; these peaks are due to both the crystalline electric field effect and the Kondo effect [8]. The resistivity decreases steeply below the Néel temperature $T_N = 10$ K. The overall behaviour is the same as that previously reported [7].

With increasing pressure P, the resistivity has a peak around 10 K, which is anomalously enhanced with increasing pressure up to 1.14 GPa, as shown in figure 2(a). With further increasing pressure, the resistivity peak is diminished and the Néel temperature becomes zero above 1.91 GPa, as shown in figure 2(b).

We define the Néel temperature as the temperature shown by arrows in figure 3. When the resistivity ρ does not show a peak as in figure 3(a), the Néel temperature is defined as a

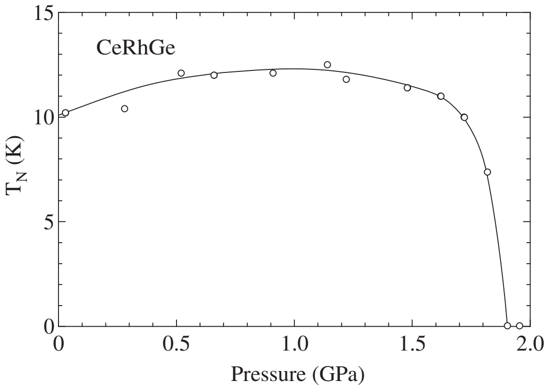

Figure 4. The pressure dependence of the Néel temperature of CeRhGe.

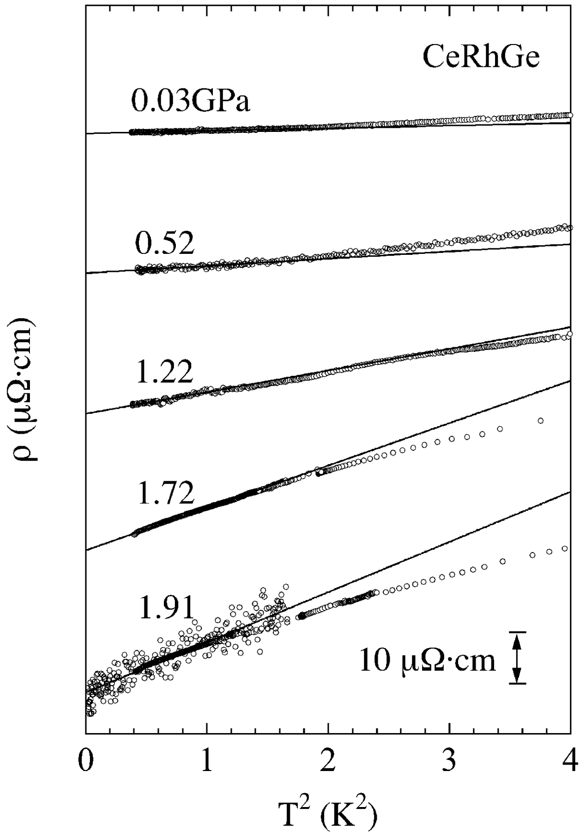

Figure 5. The T^2-dependence of the electrical resistivity under pressure in CeRhGe. Solid lines indicate the Fermi liquid relation.

minimum of $d^2\rho/dT^2$. On the other hand, the Néel temperature is defined as a maximum of $d^2\rho/dT^2$ when the resistivity has a peak as in figure 3(b).

Here we note that the resistivity peak is characteristic of an antiferromagnet with a spin density wave such as URu_2Si_2 [9]. We have tried to fit the resistivity data with the following

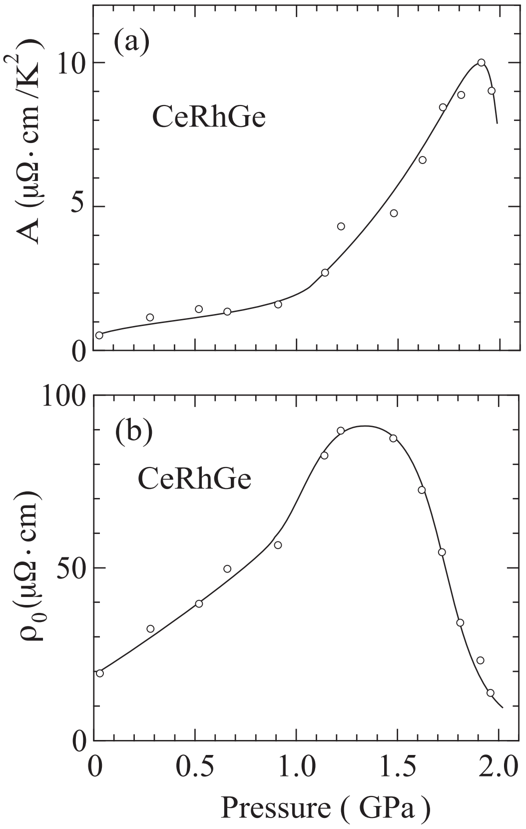

Figure 6. The pressure dependence of the A- and ρ_0-values of CeRhGe.

formula:

$$\rho = \rho_0 + AT^2 + BT\left(1 + \frac{2T}{\Delta}\right)e^{-\Delta/T}, \tag{1}$$

where a T^2-term is appropriate for Fermi liquid behaviour and the last term is applicable for an antiferromagnet with an energy gap Δ. The dotted curve in figure 3(b) is a calculated curve, with a gap $\Delta = 21$ K for $P = 1.14$ GPa.

Figure 4 shows the pressure dependence of the Néel temperature obtained above. With increasing pressure, the Néel temperature increases slightly, has a maximum at about 1 GPa, then decreases steeply with increasing pressure and becomes zero at $P_c = 1.9$ GPa.

The resistivity ρ follows the Fermi liquid relation $\rho = \rho_0 + AT^2$ below about 1 K, as shown in figure 5. The slope of T^2, namely the A-value, increases steeply above 1 GPa where the Néel temperature decreases. Figure 6 shows the pressure dependence of A and the residual resistivity ρ_0. The A-value has a maximum at P_c. On the other hand, the ρ_0-value has a maximum at 1.3 GPa and decreases with increasing pressure. We note that the A-value of 10 $\mu\Omega$ cm K^{-2} at 1.91 GPa corresponds to the value for the heavy-fermion superconductor $CeCu_2Si_2$ in the Kadowaki–Woods plot [10, 11].

We measured the resistivity at low temperatures down to 50 mK for $P = 1.91$ and 1.96 GPa to confirm the existence of superconductivity. A resistivity drop was not observed, as shown in figure 6.

Finally we will discuss the origin of the present huge resistivity peak under pressure. There are two possibilities. A huge resistivity peak was observed under pressure for the semimetal CeSb, which might be ascribed to a p–f mixing effect [12, 13]. LAPW energy band structure calculations were carried out by Harima [14] to find the electronic state of a non-4f reference compound LaRhGe—in other words, to confirm whether LaRhGe and the 4f localized compound CeRhGe are semimetallic or not. LaRhGe is found not to be a semimetal but to be a usual metal. The p–f mixing effect as found in CeSb cannot be present in CeRhGe, although the characteristic phenomena of CeRhGe are similar to those of CeSb.

Another possibility is the formation of a spin density wave. A huge resistivity peak is a characteristic of this phenomenon, leading to the gap $\Delta = 21$ K at 1.14 GPa, for example, as discussed above. Neutron scattering experiments would be necessary to confirm the existence of a spin density wave; this is left to future study.

It is thus concluded that the pressure experiment on the antiferromagnet CeRhGe indicated an extremely huge resistivity peak, most probably associated with the formation of a spin density wave. This peak is found to be diminished above a relatively small pressure of 1.9 GPa. At this critical pressure, the A-value of the T^2-term in the Fermi liquid relation becomes a maximum, corresponding to a value typical for the heavy-fermion compound $CeCu_2Si_2$.

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