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Critical electron scattering in UGe_2 near the magnetic phase transition induced by pressure

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Abstract

The electrical resistivity of single crystalline ferromagnetic UGe_2 has been measured under high pressure up to 2 GPa. It is found that the Curie temperature T_C decreases with increasing pressure and the ferromagnetism disappears at high pressure. The temperature dependent electrical resistivity is analyzed on the basis of spin fluctuation theory. The T^2 term was observed at low temperature and the coefficient shows a divergence near the critical pressure. A $T^{5/3}$ dependence in the $\rho(T)$ curve was observed below and above T_C and its pressure effect is discussed briefly.

Keywords: Electrical resistivity; Ferromagnetism; High pressure; Spin fluctuation

1. Introduction

Intermetallic compounds including Ce or U atoms have been investigated extensively because these compounds give important information for studying the role of strong electron correlations in metallic systems [1,2]. It is well known that the physical properties of these compounds having unstable f electrons are strongly affected by external forces such as pressure, magnetic field, etc. [3]. In other words, we can obtain important data for clarifying the electronic structure of these compounds through measurements taken under the influence of these external forces.

UGe_2 crystallizes in the orthorhombic structure with lattice parameters $a=4.09$ Å, $b=15.20$ Å and $c=3.96$ Å [4]. It has been reported that UGe_2 is a ferromagnet with $T_C=52$ K and its physical properties show a large anisotropy [4,5]. Recently, a highly qualified single crystal of UGe_2 was successfully prepared and exhibited an extremely large residual resistivity ratio of several hundreds.

In the present work we made an attempt to measure the temperature dependent electrical resistivity $\rho(T)$ of single crystalline UGe_2 at high pressure up to 2 GPa. The $\rho(T)$ curves are analyzed on the basis of spin fluctuation theory and the critical behavior in $\rho(T)$ near the phase boundary is discussed briefly. From the theory of critical phenomena, the similarity between the $\rho(T)$ curve and the thermal expansion coefficient is pointed out.

2. Experimental procedure

Single crystalline UGe_2 was grown by a Czochralski pulling method. The details of sample preparation and characterization have been reported elsewhere [4]. The electrical resistance along the *c*-axis was measured by using a standard d.c. four-probe method with an accuracy of 10^{-6}, in which four gold leads were attached to the sample by means of silver paste. High pressure up to 2 GPa was generated by using a tungsten carbide piston and a Cu–Be cylinder. A 1:1 mixture of Fluorinert FC 70 and FC 77 was used as the pressure transmitting medium. Details of the present high pressure apparatus have been reported previously [6].

3. Results and discussion

Fig. 1 shows an example of the electrical resistivity ρ along the *c*-axis ($J\|c$) at various pressures as a function of temperature. $\rho(T)$ at ambient pressure shows a smooth decrease with decreasing temperature and then a sudden decrease is observed near 52 K, which corresponds to the

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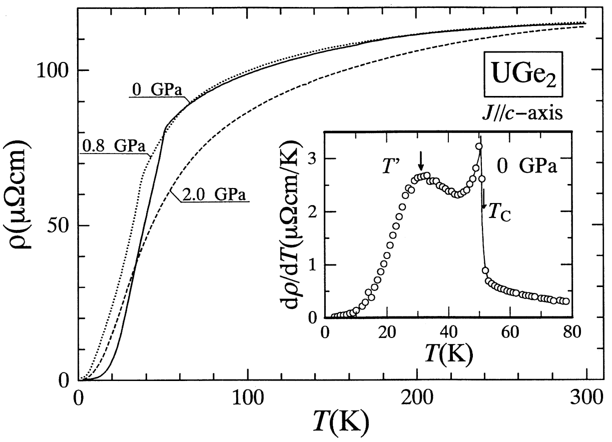

Fig. 1. Temperature dependence of the electrical resistivity ρ of UGe_2 along the c-axis at various pressures. The Curie temperature T_C and the phase transition temperature T' at ambient pressure are shown in the inset. Details of the determination of T_C and T' are described in the text.

ferromagnetic ordering. The residual resistivity ratio was about 400, which certifies the high quality of the sample. The inset in Fig. 1 shows the value of $d\rho/dT$ as a function of T at ambient pressure. There are two peaks in the temperature dependence of $d\rho/dT$, a sharp peak due to ferromagnetic ordering and a broad peak which may correspond to a kind of magnetic phase transition, but the origin is not clear at present. The Curie temperature T_C is defined as the temperature of the half value of $(d\rho/dT)_{peak} - (d\rho/dT)_{para}$, which is shown by an arrow in the inset. The transition temperature T' corresponding to the broad peak is determined as the temperature where $d\rho/dT$ begins to decrease with decreasing temperature, which is also shown in the inset. An anomaly near T' has been observed in the thermal expansion coefficient, the Hall coefficient and the thermoelectric power [4,5,7]. It is suggested that the ferromagnetism of UGe_2 is not simple because the $\rho(T)$ curve along the b-axis shows a hump below T_C which reminds us of antiferromagnetism with a gap [4]. T_C and T' are shown in Fig. 2 as a function of pressure. Both T_C and T' were found to decrease by applying pressure with coefficients $\partial T_C/\partial P = -14\,\mathrm{K\,GPa^{-1}}$ and $\partial T'/\partial P = -23\,\mathrm{K\,GPa^{-1}}$, respectively. The anomaly at T_C in the $\rho(T)$ curve due to ferromagnetic ordering disappeared above 1.5 GPa. The solid (partly dotted) curve for T_C and T' are to guide the eye. Above 1.5 GPa, UGe_2 is considered to be nearly ferromagnetic or a highly correlated compound, in which the scattering of conduction electrons is dominated mainly by spin fluctuation [4].

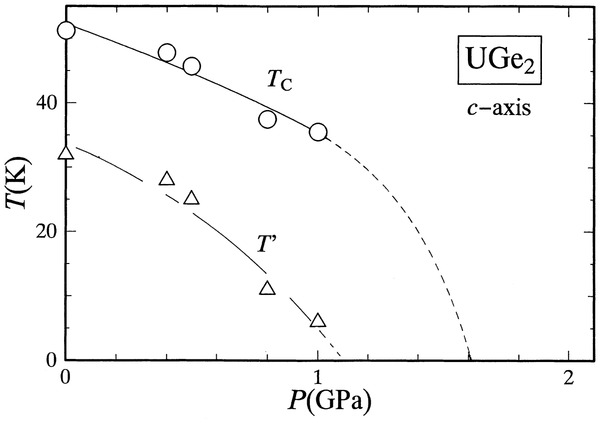

Fig. 2. The critical temperatures T_C and T' as a function of pressure.

According to the self-consistent renormalized spin fluctuation theory of Ueda and Moriya (UM) [8], the electrical resistivity $\rho(T)$ of a highly correlated itinerant ferromagnet shows a temperature dependence of T^2 in the temperature range $T \ll T_C$ and of $T^{5/3}$ both in the ranges $T \geq T_C$ and $T \leq T_C$. Since the 5f electrons in UGe_2 are considered to be strongly correlated itinerant electrons with spin fluctuations like 3d transition metals [9], the UM theory may be applicable to explain the present results.

In order to examine the T^2 dependence in the $\rho(T)$ curve due to spin fluctuation and spin wave excitation in the range $T \ll T_C$ we plotted ρ at low temperature as a function of T^2, which is shown in Fig. 3. A T^2 dependence is observed in this plot. The range showing a T^2 dependence depends on the pressure. The coefficients $A(P)$ in the equation $\rho = \rho_0 + AT^2$, where ρ_0 is the residual resistivity, are obtained by calculating the slope of the ρ vs. T^2 plot in Fig. 3. It is easily seen that the slope of the plot is large near the critical boundary of ferromagnetism. The values of A are shown in Fig. 4 as a function of pressure. A is found to increase with pressure below 1 GPa followed by a decrease above 1.5 GPa. In other words, A shows a divergence at a critical pressure P_c. The mag-

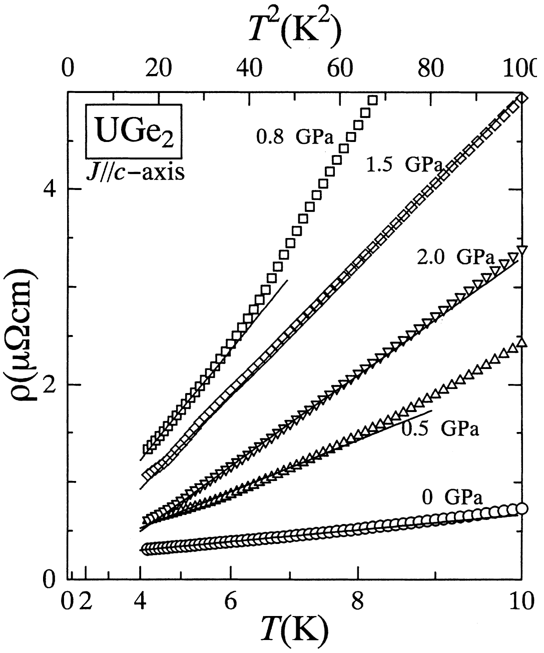

Fig. 3. ρ at low temperature in quadratic scale. The solid lines show the T^2 dependence.

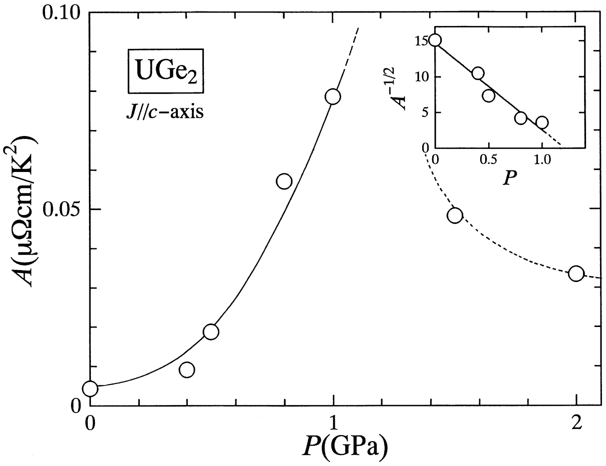

Fig. 4. The coefficient of the T^2 term as a function of pressure. The solid and dashed curves are a guide to the eye. The pressure dependence of the value of $1/A^{-1/2}$, which corresponds to the characteristic energy, is plotted in the inset.

nitude of A is known to be proportional to T_0^{-2} [3], where T_0 is a characteristic spin fluctuation temperature, i.e. $T_0 \propto A^{-1/2}$. The pressure dependence of $A^{-1/2}$ is shown in the inset of Fig. 4. $A^{-1/2}$ or T_0 is extrapolated to 0 around 1.3 GPa. In the following we assume $P_c \simeq 1.3$ GPa.

It has been reported that the value of A shows a divergence near the critical point (concentration or pressure as control parameter) where the magnetic ordering disappears or begins [10,11]. It was reported by Takahashi et al. [12] that the resistance anomaly due to ferromagnetic ordering disappears around 1.6 GPa. Considering these facts, the divergence observed in the pressure dependence of A may correspond to the disappearance of the ferromagnetism of UGe_2 around 1.3 GPa and the effect of spin fluctuation on the $\rho(T)$ curve is the most significant.

Here we examine the temperature dependence of ρ for UGe_2 at high pressure. Fig. 5 shows ρ as a function of reduced temperature $(T/T_C)^{5/3}$ at various pressures up to 1 GPa in the temperature range $0.5 \leq (T/T_C)^{5/3} \leq 1.6$. At ambient pressure the $T^{5/3}$ temperature dependence is clearly seen, as shown by the solid line used to guide the eye. As the pressure increases, the range showing a $T^{5/3}$ dependence becomes broader. The coefficients of $T^{5/3}$, B_1 below T_C and B_2 above T_C, are shown in Fig. 6. The values of B_1 and B_2 roughly increase with pressure: the increase in the magnitude of B_2 is larger than that of B_1. In the limit of critical fluctuations, B_1 is expected to be equal to B_2 [8], i.e. $B_1/B_2 = 1$. In Fig. 7 we plot B_1/B_2 as a function of pressure. It is found that B_1/B_2 extrapolates to 1 around 1.3 GPa, which is in agreement with the critical pressure P_c obtained above. This supports that the above consideration on the basis of spin fluctuation theory is reasonable even for UGe_2. But the value of P_c ($\simeq 1.3$ GPa) in the present work is different from that obtained with thermal expansion measurements ($P_c \simeq 1.8$ GPa) [7]. As was mentioned previously, there may be another kind of phase transition below T' ($\simeq 30$ K at ambient pressure) which has been reported to decrease with pressure and disappear near 1 GPa [13]. For example, at 5 K, using the results of Fig. 2, UGe_2 is ferromagnetic at ambient

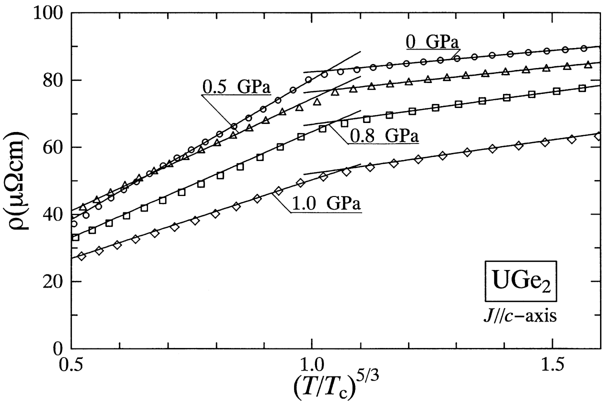

Fig. 5. ρ plotted as a function of $T^{5/3}$ around T_C. The solid lines show the $T^{5/3}$ dependence both above and below T_C.

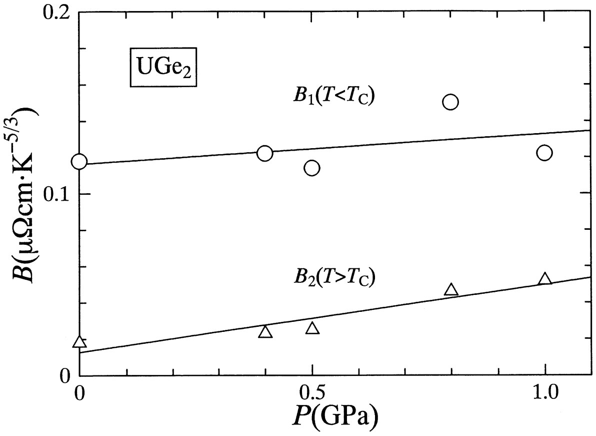

Fig. 6. Pressure dependence of the coefficient of the $T^{5/3}$ term B_1 obtained below T_C and B_2 above T_C.

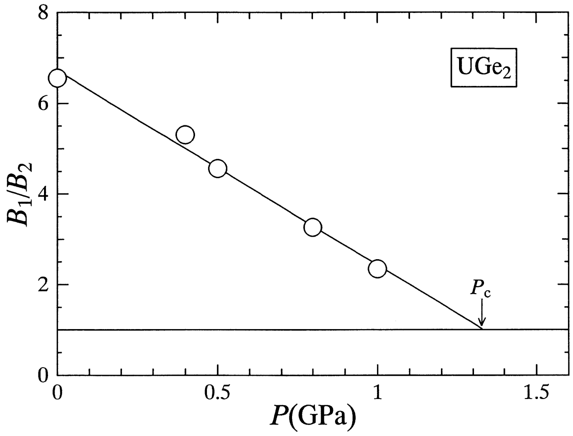

Fig. 7. The ratio of B_1 and B_2 as a function of pressure. The result of a least-squares fit is shown as the solid line and the critical pressure P_c is determined as the pressure at which it extrapolates to 1.

pressure, but as the pressure increases it undergoes a phase transition around 1 GPa, which may be a change in spin structure of second order, and then finally it becomes paramagnetic or nearly ferromagnetic above 1.8 GPa. For this reason, the phase transition at T' may make the determination of P_c difficult by electrical resistance measurements. In other words, the scattering mechanism of the conduction electrons below T' is considered to be very complicated, as suggested in the following paragraph. Thus the electronic and magnetic structure of UGe_2 in the pressure range between 1 and 1.8 GPa seems not to be simple, as pointed out previously [9].

Finally, we should mention the similarity between the critical behavior in the electrical resistivity and thermal expansion coefficients of UGe_2. It is well known that the magnetic contribution to the temperature derivative of the electrical resistivity $d\rho/dT$ should be proportional to the magnetic part of the specific heat C, $d\rho/dT \propto C$ [14]. Furthermore, the Grüneisen relation is described as

$$\alpha(T) = \frac{\kappa\Gamma}{3V}C \qquad (1)$$

where κ, V and Γ are the compressibility, the volume and the Grüneisen parameter, respectively. Since κ, V and Γ are weakly dependent on temperature, we can consider that α is roughly proportional to C. Then α is also proportional to $d\rho/dT$. Here we apply this consideration to the present results. Fig. 8 shows the temperature dependence of α_c $[=(1/c)(dc/dT)]$ and $d\rho/dT$. We can easily find the similarity between these quantities. By applying pressure, T_C decreases and the width of the peak due to ferromagnetic ordering becomes broad. It should be noted that the shape of $d\rho/dT$ at 1 GPa is significantly different from that at ambient pressure, but in the case of $\alpha_c(T)$ there is no such large difference. This suggests that the conduction electrons are scattered in a complicated way below T_C. The paramagnetic state is induced at 2 GPa and there are no clear peaks in the temperature dependence of α_c and ρ except a broad peak centered near 27 K in the $\alpha_c(T)$ curve. Such a similarity has been reported for other rare earth compounds [15].

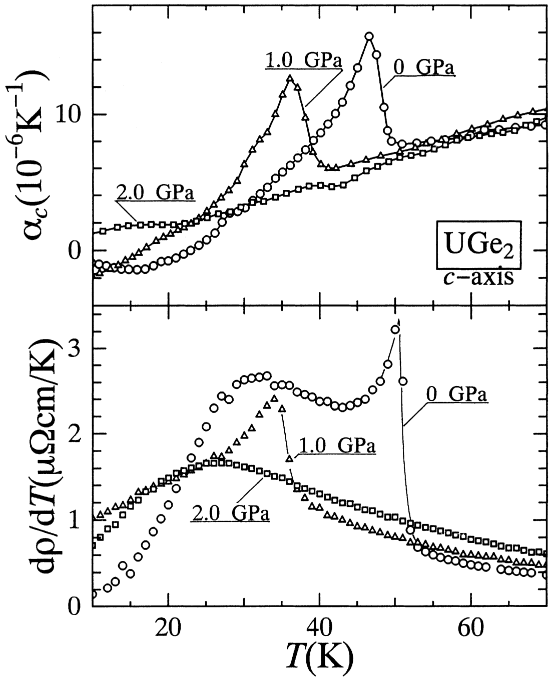

Fig. 8. Temperature dependence of (a) the thermal expansion coefficient α_c and (b) the temperature derivative of ρ at high pressure.

4. Conclusion

We have observed the electrical resistance of single crystalline UGe_2 along the c-axis. The ferromagnetism disappeared at high pressure around $P_c = 1.3$ GPa. At P_c, the coefficient of the T^2 term is found to show a divergence. The critical behavior near T_C is explained using the self-consistent renormalized spin fluctuation theory. The similarity between the thermal expansion coefficients and $d\rho/dT$ exists not only at ambient pressure but also at high pressure.

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