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2002 J. Phys.: Condens. Matter 14 10779

(http://iopscience.iop.org/0953-8984/14/44/376)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **14** (2002) 10779–10782 PII: S0953-8984(02)54111-4

Pressure-induced superconductivity in a ferromagnet, UGe$_2$: resistivity measurements in a magnetic field

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Received 27 May 2002
Published 25 October 2002

Abstract

Electrical resistivity measurements in a magnetic field are carried out on UGe$_2$ which exhibits pressure-induced superconductivity. The superconductivity is observed from 1.06 to 1.44 GPa. In the temperature and field dependences of the resistivity at $P > P_C$ where the ferromagnetic ordering disappears, it is observed that the application of an external field along the a-axis increases the coefficient A of the Fermi-liquid behaviour ($\propto AT^2$) abruptly—corresponding to the metamagnetic transition. The characteristic enhancement of H_{C2} is reconfirmed for $H \parallel a$-axis. The upper critical field of H_{C2} is anisotropic: $H_{C2}(T)$ exhibits positive curvature for $H \parallel b$-axis and $H \parallel c$-axis.

1. Introduction

Recently, pressure-induced superconductivity has been found in the itinerant ferromagnet UGe$_2$ [1]. This is a unique system, where the superconductivity seems to arise from the same electrons as produce the band magnetism.

The resistivity measurement shows that the superconductivity occurs at T_{SC} well below the Curie temperature T_C for pressure in the range $1.0 < P < 1.6$ GPa. It is confirmed by neutron scattering experiments that the ferromagnetic component of the order is still present at pressures and temperatures where the superconductivity is observed [2]. The bulk nature of the superconductivity is established from heat capacity measurements [3]. These experimental facts verify that the ferromagnetic ordering and superconductivity coexist in UGe$_2$.

It is suggested that another transition at T^* in the ferromagnetic state is related to the appearance of superconductivity [2]; that is, T_{SC} shows a maximum at the critical field for P_C^* where T^* disappears. An unusual re-entrant behaviour of the superconductivity in the magnetic field along the a-axis is observed at $P = 1.35$ GPa ($> P_C^*$), where T^* is present due to a magnetic field. These experimental facts are interpreted by considering a CDW/SDW transition to occur at T^*. Another characteristic behaviour of the transition at T^* is an anomalous increment of the magnetization. The increment of the magnetization reaches 20% of that above T^* [4, 5].

In this paper, we report the experimental results on the electrical resistivity in the magnetic field, focusing on the relation between the superconductivity and the disappearance of T^* and T_C.

2. Experimental details

A single crystal was grown by the Czochralski method in a tetra-arc furnace. The purities of the starting materials were 99.98% (U) and 99.999% (Ge). The ingot was annealed at 800 °C in a high vacuum of 5×10^{-11} Torr for seven days. For the present sample, the residual resistivity ρ_0 and the residual resistivity ratio (RRR) ($=\rho_{RT}/\rho_0$) were 0.26 $\mu\Omega$ cm and 600, respectively, at ambient pressure.

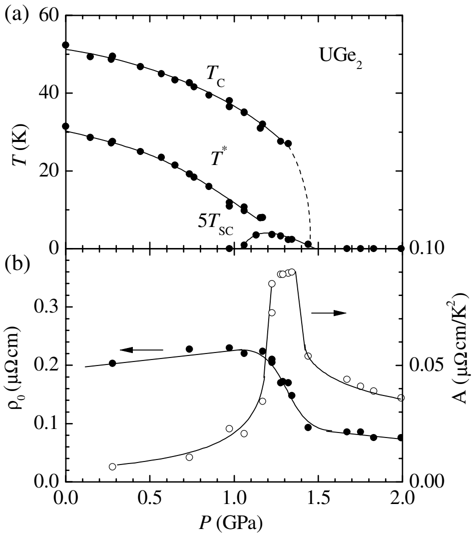
Pressure was applied by utilizing an indenter cell [6] with a Daphne oil (7373) as the pressure-transmitting medium. The pressure value was determined from the superconducting transition temperature T_{SC} of lead. The effect of a field on T_{SC} for the ferromagnetic sample was negligibly small; this was checked at ambient pressure.

3. Results and discussion

The P–T phase diagram determined from the electrical resistivity measurements is shown in figure 1(a); T_C, T^* and T_{SC} are determined from the kink and peak of $\mathrm{d}\rho/\mathrm{d}T$ and zero resistance, respectively. Superconductivity is observed from 1.06 to 1.44 GPa. T_{SC} shows a maximum at around $P_C^* = 1.22$ GPa where T^* disappears. In this experiment, a ferromagnetic–nonmagnetic transition is considered to occur at $P_C \sim 1.44$ GPa, as described later. This critical pressure is slightly different from that reported previously [1, 2], which may be attributed to sample dependence or the experimental error of the pressure determination. But it is consistent that the superconductivity disappears at around P_C and the coefficient A of the Fermi-liquid behaviour ($\propto AT^2$) retains a large value in the range $P_C^* < P < P_C$, as shown in figure 1(b). The non-Fermi-liquid behaviour expected at the quantum critical point is not observed even in the vicinity of P_C^* and P_C. It is characteristic that there is no increment of ρ_0 and A in the vicinity of $P_C \sim 1.44$ GPa, suggesting that the ferromagnetic–nonmagnetic transition at P_C is first order.

Figures 2(a) and (b) show the temperature and field dependences of the resistivity at $P = 1.67$ GPa ($>P_C$). Application of an external field along the a-axis (easy axis) increases the coefficient A abruptly at H_m due to the metamagnetic transition from the paramagnetic state at low field to the strongly polarized state at high field [7]. Further application of the field induces the transition at T^* above $H^* = 7.2$ T [2]. The appearance of T^* reduces the coefficient A and increases the residual resistivity. These behaviours of A and ρ_0 correspond to their pressure dependences at zero field, as shown in figure 1. At $P = 1.44$ GPa, the critical field H_m exists near zero field, which indicates that $P_C \sim 1.44$ GPa for the present sample. At $P = 1.22$ GPa, neither T^* nor H^* can be identified in the respective temperature and field dependences of the resistivity, indicating that $P_C^* \sim 1.22$ GPa.

The superconducting H–T phase diagram for $H \parallel a$-axis at several pressures is shown in figure 3. The enhancement of the upper critical field H_{C2} is reconfirmed at $P = 1.34$ GPa by the tuning of H^* at low temperature to 2.0 T where re-entrant behaviour of the superconductivity has been observed in [2]. The critical fields H^* at each pressure are shown in figure 4.



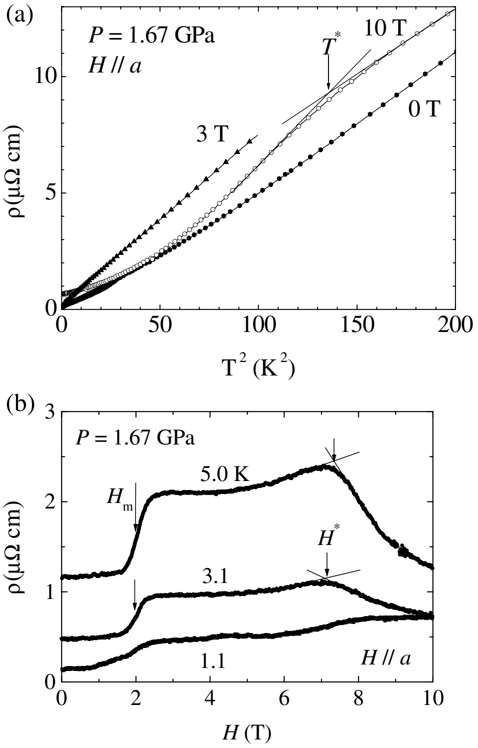


Figure 1. (a) The pressure–temperature phase diagram of UGe$_2$. (b) The pressure dependence of ρ_0 and A in the Fermi-liquid behaviour $\rho = \rho_0 + AT^2$.

Figure 2. (a) The temperature dependence of the resistivity in a magnetic field parallel to the a-axis at 1.67 GPa ($>P_C$). (b) The field dependence of the resistivity at the same pressure.

The upper critical fields H_{C2} are very sensitive to the critical field H^*. Watanabe *et al* [8] developed a microscopic theory where the CDW/SDW fluctuation enhances T_{SC} and reproduces a qualitatively anomalous superconducting H–T phase diagram. Figure 4 shows the field dependence of T_{SC} at 1.22 GPa where T_{SC} shows a maximum. The initial slope of $-\mathrm{d}H_{C2}/\mathrm{d}T$ is about 5.3 T K^{-1} for all directions, while the upper critical field H_{C2} at the lowest temperature is anisotropic. Here $H_{C2}(T)$ exhibits anomalous positive curvature for $H \parallel b$ and $H \parallel c$, which is similar to the case for the heavy-fermion superconductor UBe$_{13}$ [9]. Similar results for the anisotropic H_{C2} were obtained independently by Sheikin *et al* [10].

4. Conclusions

In the temperature and field dependences of the resistivity at $P > P_C$, abrupt variations of the coefficient A are found at H_m and H^*: the metamagnetic transitions. From these measurements in a magnetic field, the critical pressures are determined as $P_C^* \sim 1.22$ GPa and $P_C \sim 1.44$ GPa. The superconducting transition temperature T_{SC} shows a maximum at around P_C^* and disappears at around P_C, where the coefficient A maintains a maximum over the range $P_C^* < P < P_C$. The upper critical field H_{C2} is sensitive to H^* at low temperature and thus the characteristic enhancement of H_{C2} is reconfirmed. These results support the notion that critical fluctuation due to the disappearance of T^* causes superconductivity. Moreover, H_{C2} is anisotropic: $H_{C2}(T)$ exhibits positive curvature for $H \parallel b$ and $H \parallel c$.

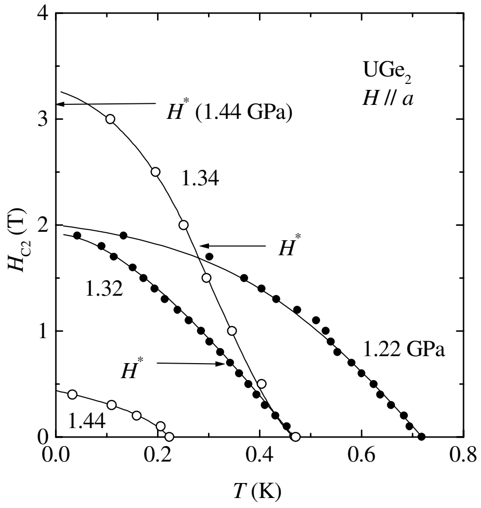


Figure 3. The superconducting H–T phase diagram for several pressures. The external field is applied parallel to the a-axis (easy axis).

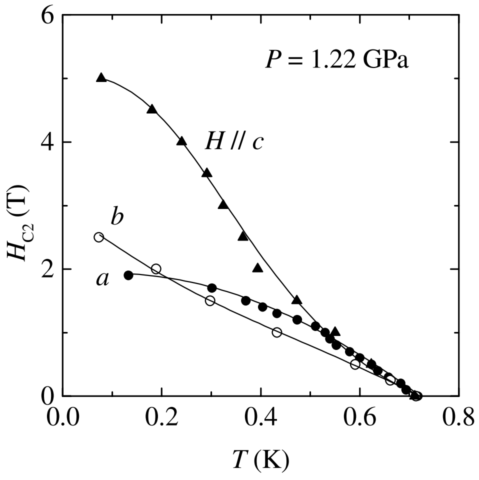


Figure 4. The anisotropy of the superconducting H–T phase diagram.

Acknowledgments

We are grateful to K Miyake and S Watanabe for helpful discussions. This work was supported by a Grant-in-Aid for COE Research (10CE2004) from the Japanese Ministry of Education, Science, Sports, Culture and Technology.

References

[1] Saxena S S *et al* 2000 *Nature* **406** 587
[2] Huxley A *et al* 2001 *Phys. Rev.* B **63** 144519
[3] Tateiwa N *et al* 2001 *J. Phys.: Condens. Matter* **13** L17
[4] Tateiwa N *et al* 2001 *J. Phys. Soc. Japan* **70** 2876
[5] Pfleiderer C and Huxley A D 2002 *Phys. Rev. Lett.* **89** 147005
[6] Eremets M I *et al* 1998 *Rev. High Pressure Sci. Technol.* **7** 469–74
[7] Huxley A *et al* 2000 *Physica* B **284–288** 1277
[8] Watanabe S *et al* 2002 *J. Phys. Soc. Japan* **71** 2489
[9] Glemot L *et al* 1999 *Phys. Rev. Lett.* **82** 169
[10] Sheikin I *et al* 2001 *Phys. Rev.* B **64** 220503