DEPENDENCE OF THE SUPERCONDUCTING TRANSITION TEMPERATURE ON THE RESIDUAL RESISTIVITY IN URhGe*

D. Aoki, A. Huxley, F. Hardy, D. Braithwaite
E. Ressouche, J. Flouquet

CEA, Départ. de Recherche Fondamentale sur la Matière Condensée, SPSMS
38054 Grenoble Cedex 9, France

J.P. Brison and C. Paulsen

CNRS, Centre de Recherches sur les Très Basses Températures
Grenoble 38042, France

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We studied the dependence of the superconducting transition temperature $T_{\rm SC}$ on the residual resistivity in the ferromagnetic superconductor URhGe. The strong suppression of $T_{\rm SC}$ caused by defects was observed. Superconductivity is completely destroyed when the mean free path falls below the superconducting coherence length, suggesting unconventional superconductivity.

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The coexistence of ferromagnetism and superconductivity is a crucial problem. In the 1970s, extensive studies were done for $4f$-electron systems, showing both superconductivity and ferromagnetism, such as $\rm ErRh_4B_4$ [1,2] and $\rm HoMo_6S_8$ [3]. In these compounds, the $4f$-electron is well localized and possesses a large magnetic moment. The superconducting critical temperature $T_{\rm SC}$ is larger than the Curie temperature $T_{\rm Curie}$, and the superconducting phase is expelled in the ferromagnetic phase because of the large internal field. Therefore, superconductivity and ferromagnetism compete with each other in this system. The discovery of superconductivity in the itinerant ferromagnet $\rm UGe_2$, however, changes the situation completely [4,5]. In $\rm UGe_2$, the superconducting phase only exists in the ferromagnetic phase, showing the coexistence of ferromagnetism and superconductivity.

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Recently we found superconductivity at ambient pressure in the itinerant ferromagnet URhGe as an another example [6]. The results of specific heat, magnetization and upper critical field are consistent with a superconducting pairing of spin-triplet type. It is known that the $T_{\rm SC}$ of unconventional superconductors is highly sensitive to the residual resistivity, because the pair-breaking occurs not only for magnetic impurities but also for non-magnetic impurities and defects. For instance, superconductivity in Sr_2RuO_4 is completely suppressed when the residual resistivity is greater than $1\,\mu\Omega\,$cm [7]. $CeRh_2Si_2$ shows no superconductivity when the residual resistivity ratio (RRR) is less than 30 [8]. Here we report the dependence of $T_{\rm SC}$ on the non-magnetic impurities or defects in URhGe determined from resistivity measurements.

Polycrystals of URhGe were prepared by radio-frequency heating of stoichiometric amounts of the constituents. The obtained crystals were annealed at 900 °C for 5 days under ultra high vacuum. X ray powder diffraction and electron microprobe analysis were carried out to check the samples. The results showed the stoichiometry to be close to the ideal without any impurity elements and phases.

URhGe crystallizes in the orthorhombic TiNiSi-type structure, forming zigzag-chains between nearest-neighbor uranium atoms. The Curie temperature $T_{\rm Curie}$ is 9.5 K and the ordered moment is $0.42\,\mu_{\rm B}$/U, suggesting weak ferromagnetism. Reflecting the crystal structure, the magnetic properties are anisotropic. The magnetic moment is directed along the c-axis and its anisotropy field is estimated to be more than 100 T. The magnetic entropy is $0.2R\ln 2$ at $T_{\rm Curie}$ [9] and the magnetization displays no saturation up to 40 T [10], indicating the itinerant nature of the $5f$-electrons. The electronic specific heat coefficient is $160\,\mathrm{mJ/K^2mol}$, which is comparable to the heavy fermion superconductor UPd_2Al_3.

We show in Fig. 1 the electrical resistivity with different residual resistivities. The resistivity steeply decreases with decreasing temperature below $T_{\rm Curie}$ and follows the relation $\rho = \rho_0 + AT^2$ at low temperature, indicating Fermi liquid behavior. The coefficient A is about $2\,\mu\Omega\,\mathrm{cm/K^2}$, which is the same for all the samples. The value of A/γ^2 is $9\times10^{-5}\,\mu\Omega\,\mathrm{cm\,K^2\,mol^2/mJ^2}$, which is considerably larger than $1\times10^{-5}\,\mu\Omega\,\mathrm{cm\,K^2\,mol^2/mJ^2}$, the universal value obtained from the Kadowaki–Woods relation [11]. This suggests that URhGe is close to the quantum critical point, because the coefficient A is predicted to diverge at the quantum critical point from SCR theory [12].

In the sample with $\rho_0 = 2\,\mu\Omega\,$cm, the resistivity starts to deviate from the T^2-behavior at 0.45 K with decreasing temperature, and becomes zero at 0.25 K, indicating superconductivity. On the other hand, the sample with $\rho_0 = 40\,\mu\Omega\,$cm shows no superconductivity down to 70 mK.

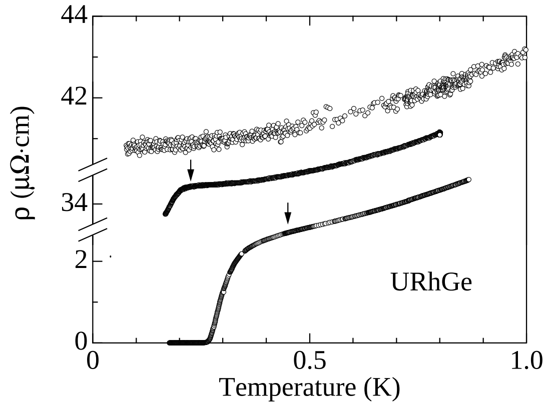

Fig. 1. Temperature dependence of the resistivity of URhGe with different residual resistivities. The arrows indicate the onset of superconductivity.

Shown in Fig. 2 is the T_{SC} as a function of the residual resistivity ρ_0, where we defined the T_{SC} as the onset of the deviation from T^2-behavior. The T_{SC} decreases with increasing ρ_0. Based on the free electron model, we can simply estimate the mean free path l at about 1000 Å for $\rho_0 = 2\,\mu\Omega\,\mathrm{cm}$ and 100 Å for $\rho_0 = 40\,\mu\Omega\,\mathrm{cm}$. Since the coherence length ξ is known to be 180 Å from the upper critical field, superconductivity occurs when the mean free path is of the order of, or larger than the coherence length. This supports the idea that URhGe can be classified as an unconventional superconductor. Contrary to the strong suppression of T_{SC}, the Curie temperature T_{Curie} shows no change with the residual resistivity.

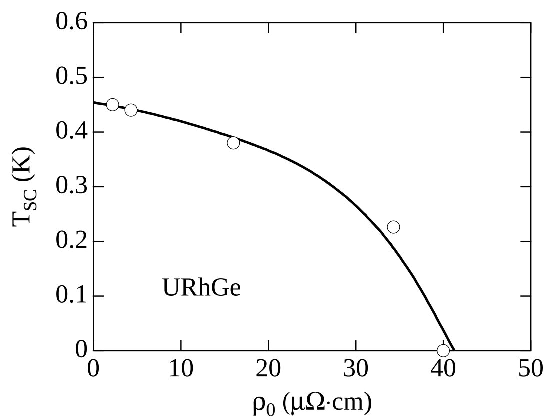

Fig. 2. Dependence of the superconducting transition temperature T_{SC} on the residual resistivity ρ_0. T_{SC} is defined as the onset of the deviation from T^2-behavior of resistivity. The solid line is a guide to the eyes.

In conclusion, we measured the resistivity in URhGe with different residual resistivities. Superconductivity is completely destroyed when the relation of $l \lesssim \xi$ is satisfied. This supports the unconventional superconductivity of URhGe.

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