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LETTER TO THE EDITOR

Pressure-induced superconductivity in ferromagnetic UIr without inversion symmetry

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Abstract
We report the discovery of pressure-induced superconductivity in ferromagnetic UIr, which lacks inversion symmetry in the crystal structure. The Curie temperature $T_{C1} = 46$ K at ambient pressure decreases with increasing pressure, reaching a value of 11 K at 1.5 GPa. It presumably decreases further up to about $P_{c1} = 1.7$ GPa. The ferromagnetic region named 'F1' exists up to P_{c1}. A second magnetic phase named 'F2' with a low ferromagnetic moment appears in the pressure range from 1.9 to 2.4 GPa. In the 'F2' phase, the magnetic transition temperature T_{C2} decreases with pressure, from 18 K at 1.9 GPa to approximately zero at $P_{C2} = 2.6$–2.7 GPa. In this critical pressure region, superconductivity appears below $T_{sc} = 0.14$ K.

Unconventional superconductivity in strongly correlated electron systems has been one of the central issues in condensed matter physics [1, 2]. Recently superconductivity has been discovered in the itinerant-electron ferromagnetic states of UGe_2 [3], URhGe [4] and $ZrZn_2$ [5], which has generated a great deal of interest as superconductivity and ferromagnetism are generally believed to be mutually exclusive. A spin triplet with a magnetically mediated pairing mechanism has been invoked to explain the unconventional superconductivity in these compounds. The existence of inversion symmetry in their crystal structure is believed to be a favourable factor for superconductivity. The absence of superconductivity in, for example, MnSi has been tentatively attributed to a lack of inversion symmetry in its crystal structure [6]. Here we report the discovery of pressure-induced superconductivity in ferromagnetic UIr, which lacks inversion symmetry, in a critical pressure region where its Curie temperature approaches zero.

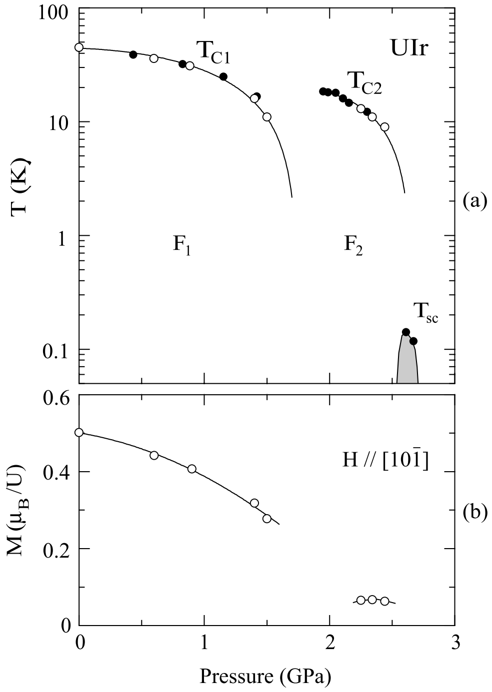

Figure 1. Pressure dependences of (a) the Curie temperatures, T_{C1} and T_{C2}, and superconducting transition temperature T_{sc}, and (b) the ferromagnetic moment in UIr. The data obtained by the magnetization and electrical resistivity measurements are shown by open and closed circles, respectively.

UIr is a 5f itinerant ferromagnet like UGe_2 with a Curie temperature $T_{C1} = 46$ K at ambient pressure [7, 8]. The crystal structure is of the monoclinic PbBi type which lacks inversion symmetry (space group $P2_1$, $a = 5.62$ Å, $b = 10.59$ Å, $c = 5.60$ Å, $\beta = 98.9°$). The Ising-like ferromagnetic moment is oriented along the [10$\bar{1}$] direction in the (010) plane, with a saturated moment of 0.5 μ_B/U. The Fermi surface mainly consists of corrugated cylindrical Fermi sheets along the [010] direction [8], reflecting the long lattice distance of 10.59 Å along the [010] direction. The cyclotron effective mass is in the range of 10–30 m_0, consistent with the electronic specific heat coefficient, $\gamma = 49$ mJ K^{-2} mol^{-1}. The single-crystal sample used in the present experiments is the same as that in [8], grown by the pulling method in a tetra-arc furnace. The residual resistivity and residual resistivity ratio were 0.5 $\mu\Omega$ cm and 200, respectively, indicating a high-quality sample. The electrical resistivity was measured from 0.1 to 300 K up to a maximum pressure of 4 GPa, while magnetization in the range from 2 to 300 K was measured up to 2.4 GPa in an indenter-type pressure cell. Pressure was determined by monitoring the superconducting transition temperature of lead.

The results of our measurements are summarized in the P–T phase diagram shown in figure 1. The Curie temperature $T_{C1} = 46$ K at ambient pressure decreases with increasing pressure, reaching a value of 11 K at 1.5 GPa. It presumably decreases further up to about $P_{c1} = 1.7$ GPa. Correspondingly the ambient-pressure saturated moment of 0.5 μ_B/U decreases considerably, as shown in figure 1(b). The ferromagnetic region existing up to P_{c1} is named 'F1'. With further increase of pressure, a second magnetic phase named 'F2' appears in the pressure range from 1.9 to 2.4 GPa. The weakly ferromagnetic state of F2 phase displays a low ferromagnetic moment of 0.07 μ_B/U at about 2.4 GPa along the [10$\bar{1}$]

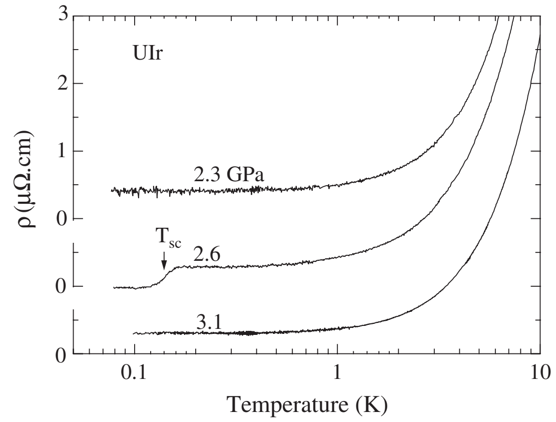

Figure 2. The temperature dependence of the electrical resistivity at selected pressures in UIr.

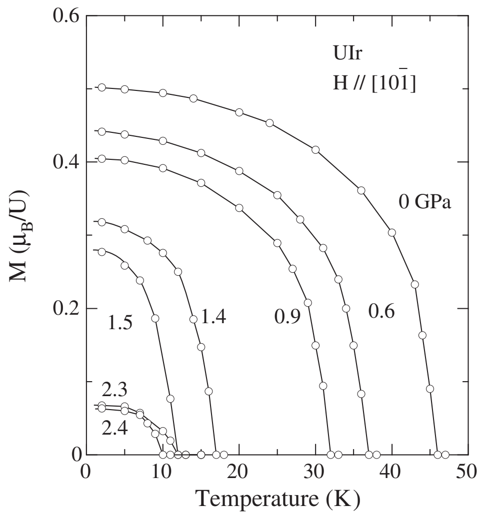

Figure 3. The temperature dependence of the ferromagnetic moment at selected pressures in UIr.

direction. In the F2 phase, the magnetic transition temperature T_{C2} decreases with pressure from 18 K at 1.9 GPa to approximately zero at $P_{C2} = 2.6$–2.7 GPa. In this critical pressure region, superconductivity appears below $T_{sc} = 0.14$ K, as inferred from the resistivity data.

Figure 2 shows the thermal variation of the electrical resistivity on a logarithmic scale of temperature between 2.3 and 3.1 GPa. The onset of superconductivity at 2.6 GPa occurs at 0.16 K and the zero-resistivity state is reached at 0.12 K. T_{sc} (=0.14 K) is defined here as the temperature corresponding to the mid-point of the superconducting transition. Our data show that the superconductivity exists in an extremely narrow pressure range from 2.60 to 2.65 GPa, most likely correlated with the phase transformation from the weak-moment ferromagnetic state to the paramagnetic state. We did not observe superconductivity for $P > P_{c2}$, at 2.9 and 3.1 GPa.

The magnetic moment was obtained from the magnetization measurements with the magnetic field applied along the easy axis, namely the [10$\bar{1}$] direction. Figure 3 shows the temperature dependence of the ferromagnetic moment at several pressures. The data show clearly that the saturated moment of 0.5 μ_B/U at ambient pressure decreases with increasing pressure, and that the F2 phase also possesses a ferromagnetic moment of 0.07 μ_B/U along $[10\bar{1}]$ for $P < P_{c2}$.

We would like to emphasize strongly the high quality of the present sample. However, the transition temperature of $T_{sc} = 0.14$ K is low. This is most likely due to a lack of inversion symmetry in its crystal structure. On the other hand, the electronic structure of UIr has a quasi-two-dimensional character, which might enhance T_{sc}, in contrast to the three-dimensional character of the electronic structure in MnSi where pressure fails to induce superconductivity [6, 9]. Very recently superconductivity has been observed in an antiferromagnet $CePt_3Si$ without inversion symmetry [10]. Theoretical considerations are needed to clarify the relation between superconductivity and lack of inversion symmetry.

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