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LETTER TO THE EDITOR

Observation of the Josephson effect in the heavy-fermion superconductor CeIrIn$_5$ above T_c

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Abstract
The Josephson effect for a heavy-fermion superconductor CeIrIn$_5$, which has two characteristic temperatures T_0 and T_c, has been investigated for CeIrIn$_5$–Cu–Nb junctions, where T_0 and T_c are the temperature of the transition to the zero-resistivity state and the bulk, thermodynamic transition temperature, respectively. For all the junctions fabricated on the (110) and (001) planes of CeIrIn$_5$, the temperature below which the Josephson effect is observed is near $T_0 = 0.8$ K and much higher than $T_c = 0.3$ K. This result suggests that at least the surface of CeIrIn$_5$ is in a superconducting state below T_0, in which phase coherence between CeIrIn$_5$ and Nb is possible.

Recently, a new family of heavy-fermion superconductors (HFS): CeTIn$_5$, where T = Rh, Ir or Co, have been discovered. CeRhIn$_5$ becomes a superconductor below 2.1 K for pressures above 17 kbar [1], while CeIrIn$_5$ [2] and CeCoIn$_5$ [3] become superconducting at ambient pressure below 0.4 K and 2.3 K, respectively. Recent studies on the NQR relaxation rate suggest an anisotropic gap in the superconducting state for these materials [4, 5]. In addition, another peculiar aspect of superconductivity has been reported for CeIrIn$_5$ [2]: although a clear superconducting transition is observed at $T_c = 0.4$ K in the measurements of the specific heat and the ac susceptibility, the electrical resistivity drops below instrumental resolution at a much higher temperature, $T_0 = 1.2$ K, without a prominent thermodynamic or magnetic signature. One possible explanation is that the inhomogeneity in CeIrIn$_5$ leads to a zero-resistivity state below T_0; if the sample contains a small amount of superconducting phase whose critical temperature is T_0, a percolating path of superconductivity along the sample is formed. This explanation, however, is questionable, since the result that the anisotropic responses of T_c and T_0 in magnetic fields are identical suggests that both transitions, at T_0 and T_c, are intrinsic and arise from a common underlying electronic structure. An interpretation in terms of local spin/charge correlations which develop well above T_c has been proposed [2]. Knowledge of some other properties which reflect both T_0 and T_c is required for an understanding of the superconductivity above T_c.

The Josephson effect between HFS and a conventional superconductor gives direct information about the order parameter of HFS. In our previous paper [6], we have reported that the two superconducting transitions of UPt_3 at zero external field are clearly seen in the Josephson effect between UPt_3 and Nb. It is interesting how the transitions at T_0 and T_c appear in the Josephson effect of $CeIrIn_5$. In this letter, SNS′ junctions, in which S($CeIrIn_5$) and S′(Nb) are separated by a normal metal N(Cu), are fabricated and the Josephson effect is investigated.

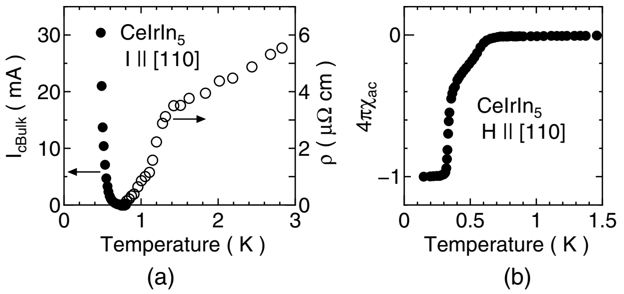
The single crystal of $CeIrIn_5$ was grown by the Czochralski pulling method in a tetra-arc furnace. A piece of crystal was cut from the ingot into a 0.95 × 1.6 × 4.4 mm parallelepiped with 1.6 × 4.4 mm faces (110) and 0.95 × 4.4 mm faces (001). The Josephson junctions were fabricated on the crystal surface. Throughout this paper the junctions are denoted as $\boldsymbol{I} \parallel [110]$ or $\boldsymbol{I} \parallel [001]$ on the assumption that the preferred current direction is perpendicular to a surface. The crystal surface was rf sputter etched by Ar ions, and then a Cu layer (normal metal) and Nb strip (s-wave superconductor) were deposited by the rf sputtering technique. The details of the sample preparation have been described in our previous paper [6]. The thicknesses d_N of Cu and the junction areas S are listed in table 1. The current leads were attached to one end of the Nb strip and the $CeIrIn_5$, and the voltage leads to the other end of the Nb strip and the $CeIrIn_5$. The electronic mean free path ℓ_N in Cu at 4.2 K was 0.4 μm ($d_N = 1.2\ \mu$m) and 0.2 μm ($d_N = 0.8\ \mu$m); this was calculated from the resistivity of the adjacent Cu strip deposited at the same time.

Table 1. Properties of $CeIrIn_5$–Cu–Nb junctions, where d_N and S are the thickness of Cu and the junction area, respectively.

Sample	Current direction	d_N (μm)	S (mm^2)
ab-0.8	[110]	0.8	0.097
ab-1.2	[110]	1.2	0.17
c-0.8	[001]	0.8	0.11
c-1.2	[001]	1.2	0.11

The critical temperature T_c was determined in an ac susceptibility measurement using an ac Hartshorn-type bridge. The absolute value of the susceptibility was determined using a piece of superconducting Sn–Pb alloy cut to the same form as the specimen as a reference material. The dc resistances of the bulk $CeIrIn_5$ and $CeIrIn_5$–Cu–Nb junctions were measured by the dc four-terminal method. The dc voltage was measured using a SQUID voltmeter which was constructed with a series combination of a standard resistor (1.65 $\mu\Omega$) and an inductance coupled to the SQUID. The voltage resolution was about 10^{-12} V. The sample was cooled down to 40 mK using a dilution refrigerator. The magnetic field in the sample region was reduced to less than 3 mOe by a μ-metal shield.

Figure 1 shows the superconducting transition of the $CeIrIn_5$ crystal used for the present investigation. Although a decrease in resistance is seen at the reported $T_0 = 1.2$ K [2], the resistance becomes zero at $T_0 = 0.8$ K. The diamagnetic susceptibility appears gradually below about 0.7 K; this is followed by a sharp transition, and a perfect diamagnetism is achieved at $T_c = 0.3$ K. The diamagnetism observed up to 0.7 K and the broad transition of the resistivity may be ascribed to the local spin/charge correlations above T_c [2], or to the inhomogeneity in the sample—that is, a broad distribution of local T_c up to 1.2 K. The critical current $I_{c\,\mathrm{Bulk}}$



(a) (b)

Figure 1. (a) The electrical resistivity ρ, critical current $I_{c\,\mathrm{Bulk}}$, and (b) ac magnetic susceptibility χ_{ac} of CeIrIn$_5$ as a function of temperature.

of bulk CeIrIn$_5$ rises slowly at first, then rapidly as the temperature is reduced, and is still increasing even at the largest value which can be allowed without heating the sample.

We show in figure 2 the typical properties of the Josephson effect between CeIrIn$_5$ and Nb. In the inset, a continuous rise in voltage is observed in the current–voltage characteristics, as the current is increased from the critical value I_c. The I–V curve is single valued and not hysteretic, which is typical of SNS′ junctions. To test the quality of the junction, the magnetic field dependence of I_c was measured. If a magnetic field is applied to a uniform junction, a Fraunhofer diffraction pattern should be observed in the magnetic field dependence of I_c. Although a falling envelope is seen with increase in the magnetic field, I_c oscillates with no definite period in figure 2. This pattern suggests that the junction is not uniform—that is, the local critical current density fluctuates spatially. One of the reasons for this fluctuation may be the roughness of the sample surface and/or the inhomogeneity in the sample, as described above.

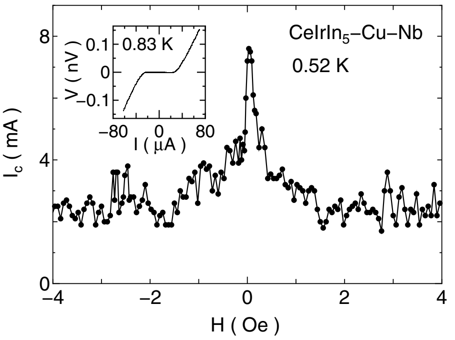


Figure 2. Typical properties of the CeIrIn$_5$–Cu–Nb junction where $I \parallel [001]$ and the Cu thickness $d_N = 0.8\ \mu$m (c-0.8). The magnetic field dependence of the Josephson critical current I_c suggests that the junction is not uniform. The solid line through the data points is a guide to the eye. Inset: the I–V characteristic showing the Josephson critical current.

Figure 3 shows the representative temperature dependence of the junction resistance R and the Josephson critical current I_c for a CeIrIn$_5$–Cu–Nb (SNS′) junction. Below the critical temperature of Nb, R consists of the resistances of the Nb–Cu boundary, Cu, the Cu–CeIrIn$_5$ boundary, and CeIrIn$_5$. When the temperature is lowered, a decrease in R due to the partial superconducting transition is observed at 1.2 K, followed by a further decrease as the resistance of CeIrIn$_5$ approaches zero. The vanishing of R due to the Josephson effect occurs below T_0. As the temperature is lowered, the Josephson critical current increases. The observation of the

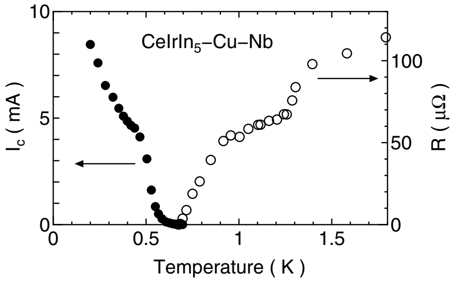


Figure 3. Typical temperature dependence of the junction resistance R and Josephson critical current I_c where $\boldsymbol{I} \parallel [110]$ and the Cu thickness $d_N = 0.8\ \mu$m (ab-0.8).

Josephson effect confirms the presence of the superconducting state above $T_c = 0.3$ K, which has been found only from the resistivity measurements.

The temperature dependence of the Josephson critical current density J_c, which is defined simply as $J_c = I_c/S$, is shown for four junctions in figure 4. Although the J_c-value is expected to become small with increase in the Cu thickness d_N, no definite d_N-dependence has been found; J_c for ab-1.2 (the junction with $\boldsymbol{I} \parallel [110]$ and $d_N = 1.2\ \mu$m) becomes the largest at low temperatures. Moreover, the junction c-0.8 with $\boldsymbol{I} \parallel [001]$ and $d_N = 0.8\ \mu$m shows the Josephson effect even above $T_0 = 0.8$ K, the temperature at which the resistance of bulk CeIrIn$_5$ vanishes in figure 1(a). This large variation of J_c from junction to junction may be explained by the assumption that there is a distribution of the local transition temperature as described above, since the Josephson effect is a probe of the order parameter only in the vicinity of the junction.

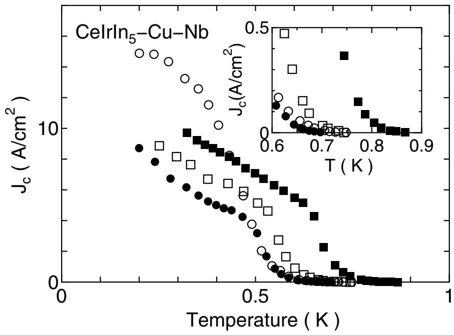


Figure 4. Temperature dependence of the Josephson critical current density J_c for four CeIrIn$_5$–Cu–Nb junctions: ab-0.8 (●), ab-1.2 (○), c-0.8 (■), and c-1.2 (□). Inset: J_c versus T near $T_0 = 0.8$ K.

If the order parameter which appears below T_0 changes its behaviour below T_c, the transition at T_c is expected to affect the temperature dependence of J_c. The broad transition up to 0.7 K in figure 1(b) probably makes it difficult to observe any abrupt change in J_c, but no unusual behaviour at $T_c = 0.3$ K has been observed within experimental accuracy. This result can be interpreted on the assumption that superconductivity appears at the surface of CeIrIn$_5$ below T_0 and the superconducting transition inside CeIrIn$_5$ occurs at T_c. However, whether we can dismiss the possibility that superconductivity above T_c is intrinsic and arises from local spin/charge correlations without global coherence, as proposed by Petrovic *et al* [2], remains open to question, since it is not yet clear how the Josephson effect appears in such a superconducting state. Even if the transition temperature at the surface is different from that of the bulk, an investigation of the origin of the difference that is found despite both transitions arising from the same underlying electronic structure [2] will be necessary.

As seen in figure 4, J_c increases slowly at first, then rapidly with decrease in the temperature. The rate of increase becomes small again at low temperatures; in particular, three junctions (not ab-1.2) show a somewhat abrupt decrease in the rate of increase at temperatures above T_c. We cannot explain the observed temperature dependence using the theory of the conventional Josephson effect, which follows.

The Josephson critical current density J_c of an SNS′ junction, where S and S′ are conventional superconductors, can be calculated by modifying that of the SNS junction derived by Clarke [7], as given by

$$J_c = A|\Delta||\Delta'|\frac{1}{\xi_N}\exp(-d_N/\xi_N) \tag{1}$$

where A is a constant and ξ_N the coherence length in N given by $\xi_N = (\hbar v_F \ell_N / 6\pi k_B T)^{1/2}$; here v_F and ℓ_N are the Fermi velocity and the electronic mean free path in N, respectively; $|\Delta|$ and $|\Delta'|$ are the order parameters at the SN and S′N interfaces, respectively. Sufficiently below T_c' for S′, where the critical temperature T_c for S is lower than T_c' for S′, J_c should vary as $|\Delta|\exp(-d_N/\xi_N)/\xi_N$. This means that the temperature dependence of J_c is determined mostly by the growth of the order parameter in S and the decay of the order parameter in N. In the case of $T \sim T_c$, J_c should be proportional to $|\Delta|$ or $|\Delta_S|/\xi_S$ in which $|\Delta_S|$ and ξ_S are the order parameter deep inside S and the Ginzburg–Landau coherence length in S, respectively. Since both $|\Delta_S|$ and ξ_S^{-1} are proportional to $(1 - T/T_c)^{1/2}$, J_c is expected to increase as $1 - T/T_c$ near T_c.

In the present CeIrIn$_5$–Cu–Nb junctions, the linear variation of J_c near T_0 is not definitely seen. The temperature dependence of J_c at low temperatures, on the other hand, seems to be determined mostly by $\exp(-d_N/\xi_N)$, as shown in figure 5. Finding a quantitative explanation for the behaviour of J_c over the whole temperature range remains a subject for future investigations.

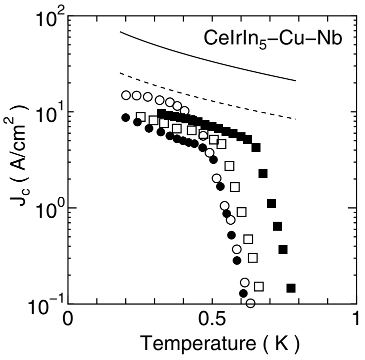


Figure 5. Josephson critical current density J_c (log scale) as a function of temperature for four CeIrIn$_5$–Cu–Nb junctions: ab-0.8 (●), ab-1.2 (○), c-0.8 (■), and c-1.2 (□). The calculated exponential dependence $\exp(-d_N/\xi_N)$ is indicated for the cases of $d_N = 0.8$ μm (——) and 1.2 μm (- - - -).

In summary, CeIrIn$_5$, which is in the zero-resistivity state below $T_0 = 0.8$ K, shows the Josephson effect well above the bulk transition temperature $T_c = 0.3$ K. This result suggests that at least the surface of CeIrIn$_5$ is in a superconducting state below T_0, in which phase coherence between $CeIrIn_5$ and Nb is possible. Considering that the Josephson effect is a probe of the order parameter only in the vicinity of the junction, the large variation of J_c from junction to junction, together with the broad superconducting transitions of the resistivity and ac susceptibility, may be ascribed to a distribution of the local transition temperature in $CeIrIn_5$.

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