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Observation of Andreev reflections and Josephson effects in point contacts between conventional and the heavy-fermion superconductor URu_2Si_2*

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We have measured the dV/dI vs. V characteristics of point contacts between the heavy-fermion superconductor URu_2Si_2 and the conventional superconductors Zn and NbTi. Contacts between URu_2Si_2 and Zn behave like a superconductor—normal metal—superconductor junction with a thick normal layer in the heavy-fermion part of the contact and show Andreev-reflection type structures related to both the heavy-fermion and the conventional superconductors. In contrast, contacts between URu_2Si_2 and NbTi become superconducting at low bias currents. The data indicate that proximity induced superconductivity is important for the coupling of the two types of superconductivity. With such contacts we also fabricated a closed-loop setup with two NbTi contacts on a URu_2Si_2 sample, which showed SQUID oscillation in a small magnetic field.

Introduction

Point-contact (PC) studies of heavy-fermion superconductors (HFS) may be a key for an understanding of their possibly unconventional superconducting state. However, up to now, only a few works concerning measurements on contacts between HFS and ordinary superconductor (SC) have been published [1–3]. These works mainly reported on investigations of the I-V characteristics of such contacts. They showed some usual for ordinary SC properties, e.g. typical values of the critical current I_c [1] and an ordinary value for Shapiro steps [2], but also some differences compared to conventional behaviour, e.g. a decrease in I_c below T_c of the HFS and nonzero resistance at $V = 0$ [2]. In addition, a very low critical current was recently observed in contacts between the HFS UPd_2Al_3 and Nb [3].

In present work we show the results of measurements on PCs between the HFS URu_2Si_2 ($T_c = 1.3$ K) and the conventional SCsZn and NbTi ($T_c = 0.87$ and 10 K, respectively). New results are the observation of the Andreev reflection structure in the dV/dI vs. V characteristics of contacts against Zn and fabrication of a SQUID using two NbTi contacts on URu_2Si_2, thus obtaining evidence for Josephson coupling in such contacts.

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Measurements and results

Contacts were obtained by touching single-crystalline URu_2Si_2 samples with thin wires of Zn or NbTi. To fabricate a SQUID, a loop of NbTi wire was pressed onto the edges of a sample in such a way that two contacts were obtained. After preparation, the samples were mounted in a dilution refrigerator. The dV/dI curves were measured using the standard lock-in technique.

Figure 1 shows typical characteristics of a URu_2Si_2–Zn PC at different temperatures. The resistance is not zero at $V = 0$ and a double-minimum structure appears on a low voltage scale (±1 mV) at temperatures below T_c of Zn. Such a dependence is typical for superconductor—normal metal (*SN*) contacts and is caused by the well-known mechanism of Andreev reflection. The distance between the minima corresponds well to the size of the energy gap of Zn. Above T_c of Zn but below T_c of URu_2Si_2, a minimum is still observed, which could be due to a smeared Andreev reflection structure of the URu_2Si_2 superconductivity. On a larger voltage scale (±20 mV), dV/dI shows an asymmetric structure, which was also observed in the [4] for PC URu_2Si_2 against normal metals. Contacts between URu_2Si_2 and NbTi show zero resistance at $V = 0$. (see Fig. 2). The corresponding critical voltage $V_c \approx 10\,\mu V$ is about one order of magnitude below the Ambegaokar–Baratoff value, which should be of order of the gap voltage of URu_2Si_2, i.e. ≈ 0.4 mV. There is a much larger structure in the characteristic of a width comparable to this value, which remained also at temperatures above T_c of URu_2Si_2. A probable origin is proximity induced superconductivity in the URu_2Si_2 sample caused by NbTi. The characteristics of a dc-SQUID made of two superconducting point contacts between URu_2Si_2 and NbTi are shown in Fig. 2 at various temperatures. We clearly observe SQUID oscillations, which vanish above the T_c of URu_2Si_2 proving that the superconductivity of the HFS is involved. From the period of oscillations of about 2–3 G we estimate that the area of the SQUID is of the order of $10\,\mu m^2$. For the characteristics shown in the Fig. 2 the NbTi loop was arranged around the corner of the sample. The contacts should therefore include an angle of about 90°, which is, however, only a rough estimate, since the mechanical technique to prepare the loop does not allow for a precise control of the geometry. Nevertheless, this experimental setup is in principle a realization of the experiment

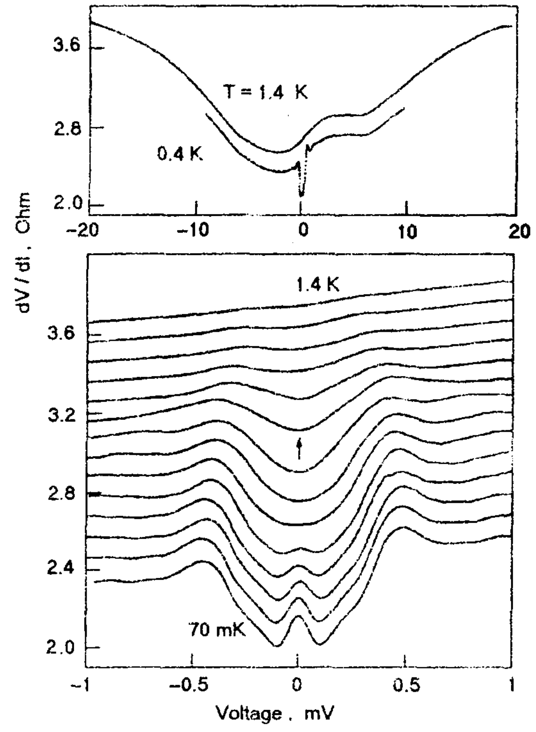

Fig. 1. Temperature dependence of the $dV/dI(V)$ for a URu_2Si_2–Zn contact between ±1 mV and ±20 mV in larger voltage scale. Temperature from top to bottom, K: 1.4, 1.3, 1.2, 1.1, 1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.07. Curves above arrow correspond to the normal state in Zn.

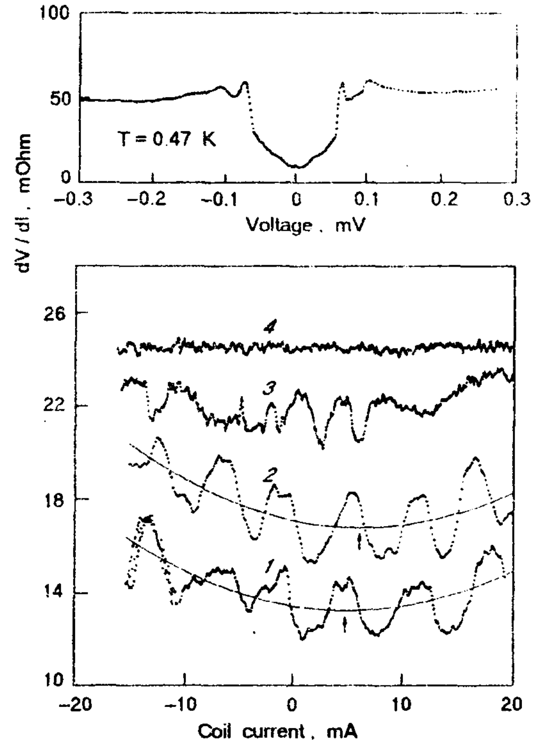

Fig. 2. The $dV/dI(V)$ for a URu_2Si_2–NbTi contact showing a zero resistance at $V = 0$ and oscillation of the dV/dI of this contact vs. current through the small superconducting coil, where the samples placed, at different temperatures *T*, K: 0.2 (*1*); 0.6 (*2*); 1.0 (*3*); 1.3 (*4*). The arrows show the position of the minimum of the background.

proposed by Sigrist and Rice [5] to determine the symmetry of the order parameter.

Discussion

For the estimation the phase difference of the order parameter between the two directions probed by the two PCs it is necessary to know the position of zero magnetic field. This position is not well-known in our experiment because of the imperfect shielding of magnetic fields, trapping of vortices near the SQUID and residual magnetic field of the small superconducting coil. Assuming that the background resistance has a minimum at zero field and a B^2 field dependence, we find zero field position as indicated by the arrows in the Fig. 2. Note that the average flux induced by the measuring current is zero, since the SQUID was driven by ac current. Interestingly, there is always a maximum of the SQUID oscillation at this position, indicating a finite phase difference, and not minimum as expected for a SQUID between two conventional SCs.

From our measurements on contacts against Zn, we can draw some conclusions concerning the structure of the PC's on URu_2Si_2. The Andreev reflection structure due to the Zn superconductivity must be ascribed to a low interface barrier, which can be only in the mechanical contact itself. Therefore, the normal conducting layer must be in the URu_2Si_2 part of the contact and we must assume that superconductivity is suppressed in a region near the contact. The width of this layer must be comparable to the size of the contact itself to prevent it from becoming superconducting. Using a Maxwell formula we obtain a value of about 350 nm for the diameter of the contact and thus also for the width of the normal conducting zone. One reason for this suppression of superconductivity could be simply the mechanical stress in the contact region in connection with the sensitivity of HFS to impurities or distortions. On the other hand, one may speculate that the development of a normal layer is connected to the magnetic properties of URu_2Si_2. For comparison, in PCs on UPt_3, which are ordered also antiferromagnetically, Andreev reflections with unusually small amplitude were observed [6], in contrast to non-magnetic UBe_{13} [7]. This fact may as well be accounted for a normal layer and suggests a connection with the magnetic order. Note that the estimated width of the normal layer is comparable to the London penetration depth.

Summary

We have shown that Josephson coupling between conventional SC and the heavy-fermion superconductor URu_2Si_2 is possible. We believe that the development of Josephson contacts with HFS is hindered by the formation of a normal zone in the heavy-fermion material. A Josephson current is then possible due to proximity induced supercondictivity in this *N*-zone. This suggests that «strong» conventional SC with high T_c should be used to obtain Josephson contacts and, in particular, to carry out the Sigrist/Rice experiment designed to measure the phase of the order parameter in HFS.

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