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PHYSICA B

Superconducting energy gap in URu₂Si₂

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Abstract

The point-contact spectroscopy has been performed on the heavy fermion system URu₂Si₂, where coexistence of antiferromagnetism and superconductivity occurs. The point contacts between a silver tip and polycrystalline URu₂Si₂ have been studied in the temperature range from 100 mK to 20 K. On differential-conductance versus applied voltage traces the formation of a (pseudo)gap is observed below the Néel temperature $T_N = 17.5$ K. This structure persists down to the lowest measured temperatures. Below the superconducting transition at $T_c = 1.3$ K a peak in the conductance emerges centered at the zero bias voltage due to the Andreev reflection on the superconducting energy gap. A compatibility of the observed superconducting energy gap with different kinds of symmetries is studied within the Blonder–Tinkham–Klapwijk theory.

Heavy fermion superconductors stand among the candidates for non-trivial superconductivity. There is experimental evidence (e.g. non-exponential behavior of the specific heat) indicating anisotropy of the superconducting order parameter with nodes or lines on the Fermi surface where the gap is zero. Point contact spectroscopy has been suitable method for studying the energy gap of heavy fermions directly. But results on the superconducting gap in URu₂Si₂ ($T_c = 1.3$ K) remains contradictory. Hasselbach et al. [1] found their data slightly more compatible with the d-wave symmetry of the superconducting gap while De Wilde et al. [2] highlighted the absence of zeros in $\Delta(\hat{k})$.

URu₂Si₂ is also a material with antiferromagnetic ordering at $T_N = 17.5$ K. The question of whether the same electronic subsystem is responsible for both transitions has not yet been solved. Ballistic point contacts, PC (electron mean free path l is much longer than the contact radius a) between normal metal and superconductor (NS) can be described within the

Blonder–Tinkham–Klapwijk (BTK) theory [3] in a barrierless regime (barrier strength $Z = 0$). An applied voltage V determines the energy gain of electrons $E \leq eV$. In the case of the isotropic energy gap for $V \leq \Delta/e$ quasiparticles cannot pass the NS interface but so-called Andreev reflection (AR) occurs. In AR the passing electron condensates to the Cooper pair and a hole is retroreflected to the normal metal. This results in an excess current and the PC conductance is twice as high as at voltages $V \gg \Delta/e$, where the quasiparticles are passing likewise in the case of NN point contact. In this manner the energy gap can be detected directly. In the case of an anisotropic gap, the situation is more complicated. The point contacts probe the order parameter within a certain spacial angle, generally unknown. The Andreev reflection on the anisotropic gap can be calculated by averaging over the anisotropic Fermi surface within the angle relevant for the particular point contact. Nevertheless, AR and the related increase in the PC conductance within the voltage $V \leq \Delta/e$ should be observable.

The polycrystalline sample of URu₂Si₂ was prepared by arc-melting stoichiometric amounts of the constituent elements under a continuously Ti-gettered argon atmosphere. After melting the starting materials

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together, the ingot was turned over and remelted. Weight losses were negligible. The point contacts between a silver tip and URu_2Si_2 were studied in the temperature range from 100 mK to 20 K. The mechanical system with differential screws in He-4 cryostat was used to form point contacts in situ above 1.5 K. The low temperature measurements were performed in the top loading dilution refrigerator (Oxford Instrument 200 TLE) and point contacts were adjusted at room temperature immediately before the top loading was immersed into the cryostat. The results represent a scan over more than 20 contacts measured in the dilution system.

In Fig. 1 the representative differential-conductance versus applied voltage traces of our PCs are shown. Below 22 K a minimum develops around the zero applied voltage. The minimum is referred to as an opening of the (pseudo)gap on the Fermi surface below the Néel temperature. The recent STM measurements [4] have shown a full ‘antiferromagnetic’ gap on the Fermi surface in the ab -plane and no gap in the c -direction. If the peak to peak distance is taken as a measure of the size of the gap $2\Delta_{\text{AF}}$, the value scattered around 15–20 meV in the PCs and the relative depth of the minimum was up to 25%. This agrees with the STM results if the averaging in crystallographic orientation in the PC on the polycrystalline sample is taken into account. Detection of the ‘antiferromagnetic’ gap should be taken as an

Fig. 1. Dynamical conductances versus voltage as a function of temperature near T_N .

indication of the spectral regime in the point contacts at this range of voltages. Otherwise, in the thermal regime, the differential conductance versus voltage has a shape similar to the temperature dependence of the conductivity and this has no minimum at low temperatures. The antiferromagnetic gap structure persists down to the lowest measured temperatures.

Below the superconducting transition at $T_c = 1.3$ K, a peak in the conductance is emerging centered at the zero bias voltage. The relative intensity of this peak at the lowest temperature scattered from one to several percent in different contacts. For further treatment the conductances were normalized at low temperatures to those $T = 1.3$ K where the peak vanishes. As a result of normalization, the peak arising on the steep background appeared symmetric as shown in Fig. 2. The conductance traces were modeled in terms of the Andreev reflection. As mentioned above due to AR the PC conductance inside the isotropic gap ($V \leq \Delta/e$)

Fig. 2. Dynamical conductances versus voltage below $T_c = 1.3$ K. Noisy, experimental curves; dashed line, s-wave fit; bold lines, d-wave fits. Curves (except at 100 mK) are vertically shifted.

should be twice the conductance at $V \gg \Delta/e$. For that a constant background was subtracted from all of the measured curves. In all of the fits accounting for the isotropic as well as for anisotropic gap the thermal smearing was taken into account. Firstly, we tried to fit our data using the conventional isotropic gap $\Delta(\hat{k}) = \Delta_0$. The fit of the BTK conductance for $\Delta = 200 \mu\text{eV}$ at $T = 100 \text{ mK}$ is shown by the dashed line. A mismatch of the fit is evident. In Hasselbach's experiment measured down to 450 mK the s- and d-wave fits were hardly distinguishable but we observed a progressive worsening of the s-wave fits down to 100 mK. Hence, we took an anisotropic gap of the d-wave symmetry in the form of $\Delta(\hat{k}) = 2\Delta k_x k_y / |k^2|$ which is among those proposed for the heavy fermion superconductors [5]. For simplicity we put the anisotropic gap to the BTK formula for the PC conductance and averaged over all angles assuming a spherical Fermi surface. This approach assumes that all of the crystallographic directions contribute. We believe this is plausible for the PC with a large diameter covering more crystallites. The resulting fits are shown in Fig. 2 at different temperatures. Despite the oversimplification in the treatment, the fit is reasonable. The resulting gaps Δ normalized to that at zero temperature are shown in Fig. 3 by circles as a function of temperature. The extrapolated value of the gap at $T = 0 \text{ K}$ amounts to $350 \mu\text{eV}$.

It is noteworthy that apart from the most commonly observed triangular shape of the conductance peak indicating the gap anisotropy, we also observed the PC with a flat maximum at zero bias voltage. We believe

that in that particular case, a small portion of the $\hat{k}$ -space with a full gap was scanned by the PC.

The surface S , enclosed between the tunneling conductance trace at low temperature and the normal state conductance (the latter equal to 1 in Fig. 2) represents the excess current I_{exc} . This measure is directly proportional to the value of the energy gap at particular temperature [3]. The S surfaces were integrated with the results normalized to S_0 -extrapolated value at zero temperature and are shown in Fig. 3 for the data from Fig. 2 and for another PC. A significant deviation from the temperature dependence of the gap predicted for the BCS-type isotropic superconductor is observed. A depression of the gap is faster in our case similar to the measurements on UPt_3 [2].

The value of the reduced gap $2\Delta/k_B T_c$ obtained from our data amounts to 6.0. Again it is considerably different from the BCS prediction giving 3.52 for the weak coupling limit. Recent analysis of possible symmetries of the gap in superconducting URu_2Si_2 in modeling the specific heat [6] has shown that the symmetry $2\Delta k_x k_y / |k^2|$ is among the best to explain the temperature dependence of the specific heat. The calculated value of the reduced gap was 5.14 in that case but the best fit to the specific heat was carried out for the value equal to 1.14.

In conclusion, experimental evidence for non-trivial symmetry of the superconducting order parameter was found.

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Fig. 3. Temperature dependence of the superconducting energy gap for different PCs.