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Superconducting gap and pair breaking in $CeRu_2$ studied by point contacts

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The superconducting gap in a $CeRu_2$ single crystal is investigated by point contacts. BCS-like behavior of the gap Δ in the temperature range below T_c^* ($T_c^* < T_c$, where T_c is the critical temperature) is established, indicating the presence of a gapless superconductivity region (between T_c^* and T_c). The pair-breaking effect of paramagnetic impurities, supposedly Ce ions, is taken into consideration using the Scalski–Betbeder-Matibet–Weiss approach based on Abrikosov–Gorkov theory. It allows us to recalculate the superconducting order parameter Δ^α (in the presence of paramagnetic impurities) and the gap Δ^p (in the pure case) for the single crystal and for the previously studied polycrystalline $CeRu_2$. The value $2\Delta^p(0) \approx 2$ meV, with $2\Delta^p(0)/k_B T_c \approx 3.75$, is found in both cases, indicating that $CeRu_2$ is a «moderate» strong-coupling superconductor.

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Introduction

The superconducting gap Δ of $CeRu_2$ has been evaluated by point-contact Shottky tunneling (PCT) [1], break-junction tunneling (BJT) [2], point contact spectroscopy (PCS) [3], and scanning tunneling microscope (STM) experiments [4]. The necessity of new PCS experiments is due to the discrepancy between the results obtained by different experimental methods. From the PCT measurements $2\Delta(0)/k_B T_c$ is estimated as 6.6 ± 0.6, while the BJT experiments yielded $2\Delta(0)/k_B T_c = 4.4$. These values are remarkably larger than our previous PCS result 3.1 ± 0.1 [3], which is more consistent with the recent tunneling data $2\Delta(0)/k_B T_c = 3.3$ [4]. The measurements of the superconducting gap were performed by different methods and on samples of different quality. In this paper we present a comparison of the superconducting gap behavior of samples with different quality studied by one method. We also propose a procedure for Δ correction based on taking pair-breaking effects into account, which results in almost equal gap values for both samples.

Experiment and results

We have studied the superconducting gap in single crystal $CeRu_2$ samples by measuring dV/dI for S–c–N (here S is a superconductor, c is a constriction, and N is a normal metal) point contacts. The single crystal was grown by the Czochralski pulling method in a tetra-arc furnace. Its residual resistivity ratio (RRR) is 120, residual resistivity $\rho_0 = 1$ μΩ·cm, and $T_c = 6.3$ K. The polycrystalline $CeRu_2$ studied in [3] had $RRR = 14$, $\rho_0 = 31.5$ μΩ·cm, and $T_c = 6.2$ K, that is it had much lower quality. The point-contact characteristics presented were obtained on cleaved surface of $CeRu_2$ for both samples*. The samples were cleaved

* The sample size was about 1×1×5 mm.

in air at room temperature. The PCs were prepared by touching this surface with the edge of an Ag or Cu counterelectrode, which were cleaned by chemical polishing. The experimental cell with the sample and counterelectrode was immersed directly in liquid ^{4}He to ensure good thermal coupling. The measurements were carried out in the temperature range 1.7–6.7 K. The differential resistance dV/dI of the PCs was recorded versus the bias voltage using a standard lock-in amplifier technique, modulating the direct current I with a small 480 Hz ac component.

The Blonder, Tinkham, and Klapwijk (BTK) theory [5] is commonly used to describe the behavior of the current–voltage characteristics of clean S–c–N microconstrictions. As in our previous publication [3], here we have used this model, which takes into account the Andreev reflection on the S–N interface [5], to fit the measured $dV/dI(V)$ curves of PCs. According to the theory [5] a maximum at zero-bias voltage and a double-minimum structure around $V \sim \pm\Delta/e$ on the dV/dI curves manifests the Andreev reflection process with a finite barrier strength parameter Z. It follows from the equations for the current–voltage characteristics

$$I(V) \sim \int_{-\infty}^{\infty} T(E)[f(E-eV) - f(E)]\, dE\,, \qquad (1)$$

$$T(E) = \frac{2\Delta^2}{E^2 + (\Delta^2 - E^2)(2Z^2+1)^2}\,, \quad |E| < \Delta\,,$$

$$T(E) = \frac{2|E|}{|E| + \sqrt{E^2 - \Delta^2}\,(2Z^2+1)}\,, \quad |E| > \Delta\,,$$

where $f(E)$ is the Fermi distribution function. The broadening of the quasiparticle density of states $N(E, \Gamma)$ in the superconductor was taken into account according to Dynes et al. [6]:

$$N(E, \Gamma) = \mathrm{Re}\left\{\frac{E - i\Gamma}{\sqrt{(E-i\Gamma)^2 - \Delta^2}}\right\}, \qquad (2)$$

where Γ is the broadening parameter.

In Fig. 1,*a* a series of experimental $dV/dI(V)$ curves of PCs based on the $CeRu_2$ single crystal are presented along with the fitted ones for different temperatures. The good agreement between experimental and theoretical curves allowed us precisely to determine Δ along with its temperature dependences from calculations according to (1), (2). The average value of the gap Δ of the $CeRu_2$ single

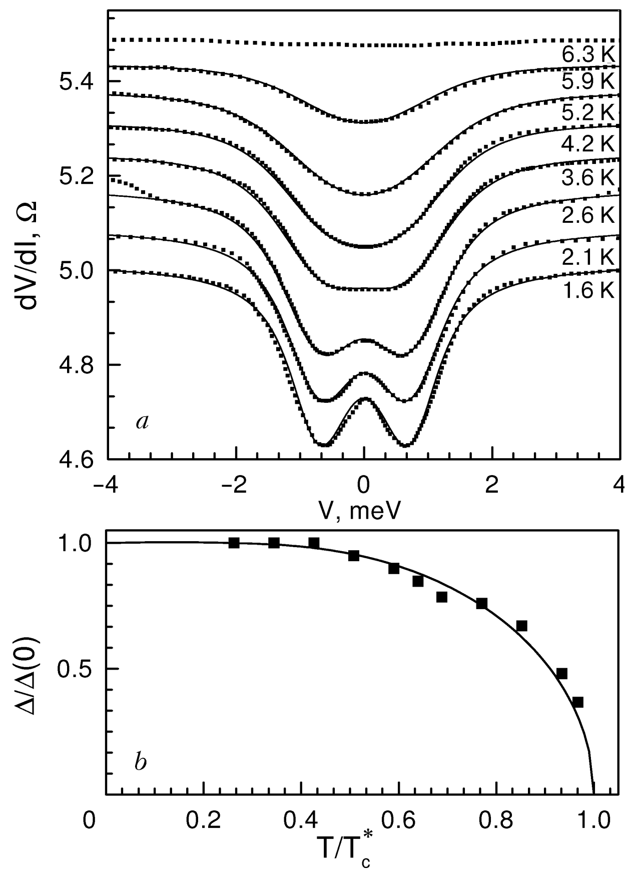

Fig. 1. Temperature dependence of the experimental $dV/dI(V)$ curves (squares) for a $CeRu_2$–Ag point contact with $R_N = 5\ \Omega$ along with the fit using Eqs. (1), (2) with $\Gamma \cong 0.13$ meV and $Z = 0.43$ (solid lines). The curves are shifted vertically for clarity (*a*). Temperature dependence of the superconducting gap Δ extracted from the fit in Fig. 1,*a*. $\Delta(0) = 0.79$ meV and $T_c^* = 6.1$ K, with $2\Delta(0)/k_B T_c^* = 3.05$. The solid line is the BCS curve (*b*).

crystal extracted from the fit for 5 PCs is (0.83 ± 0.07) meV, with $2\Delta(0)/k_B T_c^* = 3.23 \pm 0.23$ and $T_c^* = (5.9 \pm 0.2)$ K. The maximum $\Delta(0)$ was 0.95 meV and $T_c^* = 6.1$ K, where T_c^* is the extrapolated temperature at which the gap drops to zero (see Fig. 1,*b*). The temperature dependence of the superconducting gap extracted from the curves on Fig. 1,*a* is presented in Fig. 1,*b* and has a BCS-like behavior as in the polycrystalline sample [3]. The extrapolated critical temperature T_c^* for single crystal is higher and the gapless region is smaller than in the polycrystalline sample [3]. The gap value (averaged for 5 PCs as well) grew from (0.51 ± 0.07) meV for the polycrystal to the value indicated above for the single crystal of $CeRu_2$. This has a natural explanation considering the difference in the quality of the samples. The contacts made on the more perfect single-crystal $CeRu_2$ exhibited better superconducting properties than those with the polycrystal.

In our previous paper [3] the presence of a region of gapless superconductivity in $CeRu_2$ between T_c^* and T_c was proposed to explain why $T_c^* \neq T_c$. The gap was assumed to be suppressed by the local magnetic moments, presumably Ce, distributed randomly in the contact region. That is, because of the lower purity (quality) of the polycrystal some of the Ce ions could be impurities.

The well-known Abrikosov–Gorkov (AG) theory of a superconductor containing paramagnetic (PM) impurities [7] was considered for explaining a gapless state in $CeRu_2$. The theory describes a situation when in the presence of PM impurities the gap Δ in the excitation energy spectrum drops to zero at a transition temperature T_c^* although the material is still a superconductor in the sense of having pair correlations. The transition temperature T_c^* is lower than the critical temperature T_c, and a range of temperatures between T_c^* and T_c where Δ is zero for any value of the impurity concentration exists. The Scalski–Betbeder-Matibet–Weiss (SBMW) approach [8] based on AG theory allows us to take into account a pair breaking caused by spin-exchange scattering. As a measure of this effect produced by PM impurities the inverse collision time for exchange scattering $\alpha = \hbar/\tau_{ex}$ was used. The advantage of the SBMW approach is the natural way in which the distinction between the energy gap Δ and the order parameter Δ^α arises when the effect of PM impurities on the density of states is taken into account. The SBMW theory allows us to calculate the order parameter Δ^α of a superconductor with PM impurities by transformation of the original expression (4.8) from [8]:

$$\Delta(T, \alpha) = \Delta^\alpha(T, \alpha)\left[1 - \left(\frac{\alpha}{\Delta^\alpha(T, \alpha)}\right)^{2/3}\right]^{3/2}$$

into the foolowing form:

$$\Delta^\alpha(T, \alpha) = \Delta(T, \alpha)\left[1 + \left(\frac{\alpha}{\Delta(T, \alpha)}\right)^{2/3}\right]^{3/2} . \quad (3)$$

In (3) the pair-breaking parameter α is unknown. It was determined from the T_c^*/T_c^p and $\Delta(0)/\Delta^p(0)$ versus $\alpha/\Delta^p(0)$ curves (the superscript p indicates a pure superconductor; we also suppose that $T_c^p \equiv T_c$) shown in Fig. 2. The value of T_c^* was taken from the experimental temperature dependence of Δ as the value extrapolated according to the BCS theoretical curve (see Fig. 1,*b*). Then $\alpha/\Delta^p(0) = \beta$ corresponding to T_c^*/T_c^p was determined for the particular point contact, and $\Delta(0)/\Delta^p(0) = \gamma$ at the value of $\alpha/\Delta^p(0) = \beta$ determined was specified. The $\Delta(0)$ value was taken from a fit of the experimental curve. Thus we obtained $\Delta^p(0) = \Delta(0)/\gamma$ and, hence, $\alpha = \Delta^p(0)\beta = \Delta(0)\beta/\gamma$. The order parameter $\Delta^\alpha(0)$ was found from (3) to be (0.99 ± 0.05) meV for the single crystal and (0.87 ± 0.1) meV for the polycrystal. Figure 3 shows the results of the calculations of $\Delta^\alpha(T)$ from (3). The temperature dependences of the parameter Δ^α both for the purer sample and for the less perfect one have behavior close to the BCS curve.

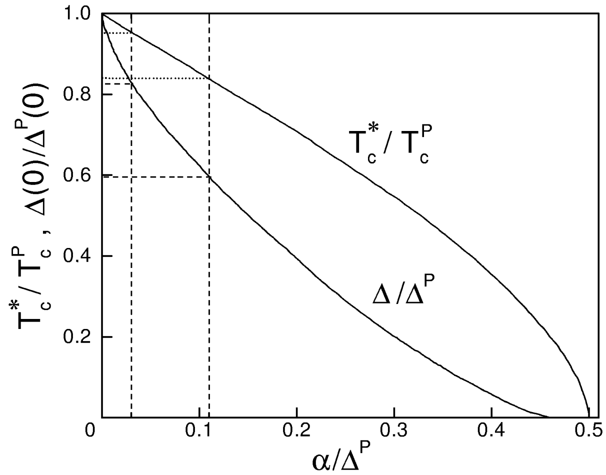

Fig. 2. The T_c^*/T_c^p and $\Delta(0)/\Delta^p(0)$ vs. $\alpha/\Delta^p(0)$ curves from Ref. 8. The dashed vertical lines indicate $\alpha/\Delta^p(0) = \beta = 0.03$ for the single crystal from Fig. 1 and $\beta = 0.11$ for the polycrystal from Fig. 1 in Ref. 3 as determined using the experimental values of T_c^*/T_c^p (dotted horizontal lines). Dashed horizontal lines show the $\Delta(0)/\Delta^p(0) = \gamma$ determined values.

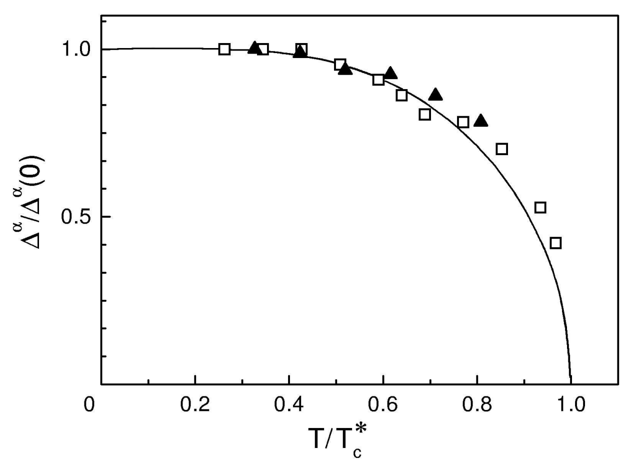

Fig. 3. Temperature dependences of the order parameter $\Delta^\alpha(T)$ for the single-crystal sample from Fig. 1 (open squares) and for the polycrystalline sample from Fig. 1 in Ref. 3 (triangles).

The order parameter $\Delta^p(0)$ of the pure superconductor can be determined from Fig. 2 using the value of γ or calculated from the expression (3), (5) of Ref. 8:

$$\ln\left(\frac{\Delta^\alpha(0,\alpha)}{\Delta^p(0)}\right) = -\frac{\pi}{4}\frac{\alpha}{\Delta^\alpha(0,\alpha)},$$

which transforms into

$$\Delta^p(0) = \Delta^\alpha(0,\alpha)\exp\left\{\frac{\pi}{4}\frac{\alpha}{\Delta^\alpha(0,\alpha)}\right\}.$$

The value of $\Delta^p(0)$ has less scatter in comparison with $\Delta^\alpha(0)$ and is about (1.02 ± 0.05) meV with $2\Delta^p(0)/k_BT_c = 3.8 \pm 0.2$ for the single crystal and $\Delta^p(0) = (0.99 \pm 0.13)$ meV with $2\Delta^p(0)/k_BT_c = 3.7 \pm 0.5$ for the polycrystal.

Discussion and conclusions

As was shown earlier [3,4] and in this paper the temperature dependence of Δ in $CeRu_2$ has a BCS-like behavior, but with a lower critical temperature T_c^*. Because of the difference in T_c^* for the samples of different quality we can conclude that in the cleaner one the influence of impurities on the superconductivity is also weaker. Pair-breaking effects in the contact area can be caused by the randomly distributed local magnetic moments. It was noted by Joseph et al. [9] that a Ce-rich solid solution is present as a second phase in $CeRu_2$ in an amount up to 10% in the samples of low quality. This means that pair-breaking effects and gapless superconductivity in the compound more probably are connected with the influence of Ce impurities. Calculations based on the SBMW approach gave very close values of $\Delta^p(0)$ and $2\Delta^p(0)/k_BT_c$ for poly- and single crystals. This supports our assumptions about the influence of paramagnetic impurities on superconductivity in $CeRu_2$ and gives a method of Δ correction. This method of recovering the superconducting parameters from point-contact $dV/dI(V)$ characteristics can theoretically be improved by including in the BTK fit a density of states modified by the pair-breaking effect.

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