

HINTS AT UNCONVENTIONAL SUPERCONDUCTIVITY OF THE HEAVY-FERMION SUPERCONDUCTOR CeCoIn_5 *

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We report on investigations of CeCoIn_5 in the superconducting state by point-contact spectroscopy. Andreev reflection of quasiparticles at a normal metal/superconductor interface leads to characteristic features in the differential resistance dV/dI as a function of applied bias V . We measured spectra which show either a reduced resistance for bias $|V| < \Delta/e$ with a double minimum at $V \approx \pm\Delta/e$ or a single minimum of dV/dI for $V = 0$, *i.e.*, a zero-bias anomaly. Both features are weakened with increasing temperature and vanish close to T_c . The observation of a zero-bias conductance anomaly is expected only if the order parameter exhibits a sign change as a function of $\vec{k}$. Andreev reflection of the quasiparticles at the surface leads to a surface bound state which is detected in the dV/dI vs V spectra. Therefore the data support unconventional superconductivity in CeCoIn_5 .

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1. Introduction

The ternary rare-earth compound CeCoIn_5 is a heavy-fermion superconductor with a superconducting transition temperature $T_c = 2.3$ K [1], the highest transition temperature among the heavy-fermion superconductors, and a linear coefficient of the specific heat $\gamma(T_c) = 350$ mJ/molK² [2]. There

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is strong experimental evidence that superconductivity in this material is unconventional. There is an enormous jump ΔC in the specific heat at T_c with $\Delta C/\gamma T_c = 4.5$ while $\Delta C/\gamma T_c = 1.43$ is predicted in weak-coupling BCS theory. In the superconducting state, power-law behavior of the specific heat close to T^2 [2,3] and of the thermal conductivity close to T^3 [3] give evidence that the superconducting order parameter has line nodes. From the observation of a clear fourfold symmetry of the thermal conductivity in the superconducting state an order-parameter with the angular position of the nodes along the $(\pm\pi, \pm\pi)$ direction has been proposed [4] which belongs most likely to $d_{x^2-y^2}$ symmetry. From NMR measurements [5] which showed a vanishing spin susceptibility for $T \ll T_c$, a spin-singlet-pairing state is inferred as well.

2. Results and discussion

Point-contact spectroscopy is a very suitable tool to study the order-parameter symmetry through the mechanism of Andreev reflection (AR). Heterocontacts between the superconducting sample (S) and a normal-metal (N) counterelectrode Pt were established in a ^4He bath cryostat at lowest $T = 1.5\text{ K}$ by means of a mechanical differential screw mechanism. The typical contact resistances range between 1 and $130\ \Omega$. The differential resistance dV/dI of the contacts as a function of applied bias V was measured with a standard lock-in technique. Figure 1 gives an overview of the point-contact spectra at $T \approx 1.5\text{ K}$ at different points on the surface. For comparison, the spectra have been normalized to the differential resistance at $V = -5\text{ mV}$ and shifted with respect to each other. The main result is that two distinctly different types of spectra are observed. Curves displayed in panel (a) represent spectra which exhibit a double-minimum structure, while curves displayed in panel (b) represent spectra which show a single minimum in dV/dI centered at $V = 0$, and shoulders symmetric in V at higher bias. In both cases, the features are related to superconductivity as they become weaker with increasing T and vanish near T_c (see Fig. 2(a) and (b)).

Minima at finite V in the differential resistance are expected for N/S point contacts due to Andreev reflection at the N/S interface for both conventional [6] and unconventional [7] superconductors. This scattering process, where an electron is injected and a hole is retro-reflected with probability R_A , leads in isotropic fully gapped superconductors to a reduction of dV/dI for voltages $< \Delta/e$. A finite but small probability $1 - R_A$ of normal reflection due to an interface barrier increases the zero-bias resistance and leads to the characteristic double-minimum feature with minima at $\pm\Delta/e$. Qualitatively, the same general behavior is expected for unconventional superconductors with a k -dependent gap function $\Delta = \Delta(\vec{k})$, although the

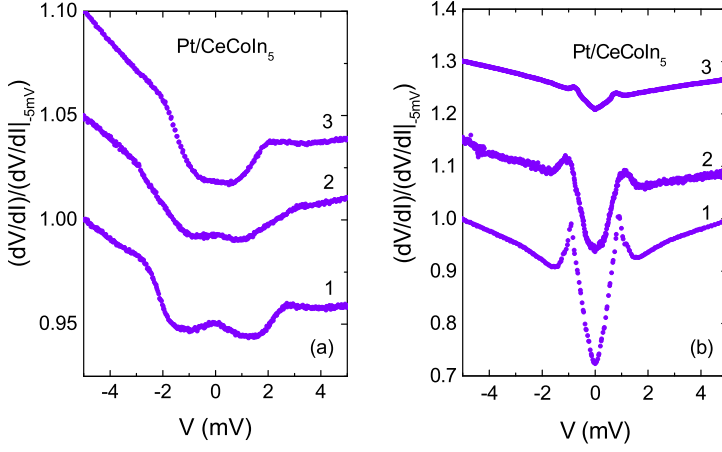


Fig. 1. Differential resistance dV/dI vs voltage V of point contacts between CeCoIn_5 and Pt at $T = 1.5$ K. The contact resistance is $R_0 = 3.3 \Omega$ (1), 2.1Ω (2), and 3.6Ω (3) for curves in panel (a) and $R_0 = 4.2 \Omega$ (1), 1.2Ω (2), and 1.6Ω (3) for curves in panel (b).

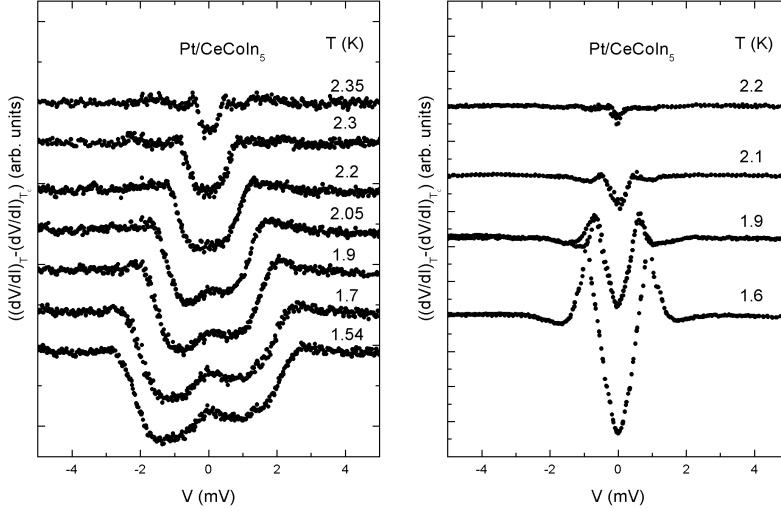


Fig. 2. Temperature dependence of both types of structures in the differential resistance dV/dI vs V .

“transparency” of the junction for AR has to be determined self-consistently to take into account that the interface itself might be pairbreaking for some order-parameter symmetries. In principle, from the width of the structure

and the position of the minima, the gap value Δ can be inferred by fitting the curves, although the exact value depends on the choice of the order parameter. A rough estimate shows that Δ is well above the weak-coupling limit $2\Delta = 3.5k_{\text{B}}T_c = 0.69$ meV.

The observation of a zero-bias conductance anomaly (ZBA) is expected only if the order parameter exhibits a sign change as a function of $\vec{k}$. Andreev reflection of the quasiparticles at the surface leads to a surface bound state which is detected in the dV/dI vs V spectra. It was shown [8] that for the $d_{x^2-y^2}$ symmetry, the occurrence of a ZBA depends on the direction of current flow with respect to the crystallographic axis. For current injection along the [100] direction, no zero-bias anomaly is detected because no surface bound state is formed. In contrast, along [110], the order parameter exhibits a sign change and, therefore, a surface bound state at zero energy is formed which is seen in the spectra as a enhanced conductance at zero bias, *i.e.*, a single minimum in dV/dI .

3. Conclusion

In summary, directly probing the superconducting energy gap of CeCoIn₅ by means of point-contact spectroscopy gives strong support of an unconventional pairing state. The most convincing indication clearly comes from the occurrence of a zero-bias anomaly. The undefined direction of current flow in the experiment, however, prevents a definite assignment of the order-parameter symmetry.

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REFERENCES

- [1] C. Petrovic *et al.*, *J. Phys.: Condens. Matter* **13**, L337 (2001).
- [2] V.S. Zapf, *et al.*, *Phys. Rev.* **B65**, 014506 (2001).
- [3] R. Movshovich *et al.*, *Phys. Rev. Lett.* **86**, 5152 (2001).
- [4] K. Izawa *et al.*, *Phys. Rev. Lett.* **87**, 057002 (2001).
- [5] Y. Kohori *et al.*, *Phys. Rev.* **B64**, 134526 (2001).
- [6] G.E. Blonder, M. Tinkham, T.M. Klapwijk, *Phys. Rev.* **B25**, 4515 (1982).
- [7] Chr. Bruder, *Phys. Rev.* **B41**, 4017 (1990).
- [8] M. Fogelström *et al.*, *Phys. Rev. Lett.* **79**, 281 (1997).