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

G. Goll, H. v. Löhneysen†

Physikalisches Institut, Universität Karlsruhe, 76128 Karlsruhe, Germany

V.S. Zapf, E.D. Bauer and M.B. Maple

Department of Physics and Institute for Pure and Applied Physical Sciences
University of California, San Diego, La Jolla, CA 92093, USA

*(Received July 10, 2002)*

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 $CeCoIn_5$.

PACS numbers: 74.70.Tx, 74.20.Rp, 73.40.Jn, 74.80.Fp

## 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 $\gamma(T_c) = 350\,mJ/molK^2$ [2]. There

* Presented at the International Conference on Strongly Correlated Electron Systems, (SCES 02), Cracow, Poland, July 10–13, 2002.

† Also at: Forschungszentrum Karlsruhe, Institut für Festkörperphysik, D-76021 Karlsruhe, Germany

is strong experimental evidence that superconductivity in this material is unconventional. There is an enormous jump $\Delta C$ 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 $^4$He bath cryostat at lowest $T = 1.5$ K by means of a mechanical differential screw mechanism. The typical contact resistances range between 1 and 130 Ω. 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 $T \approx 1.5$ K at different points on the surface. For comparison, the spectra have been normalized to the differential resistance at $V = -5$ 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

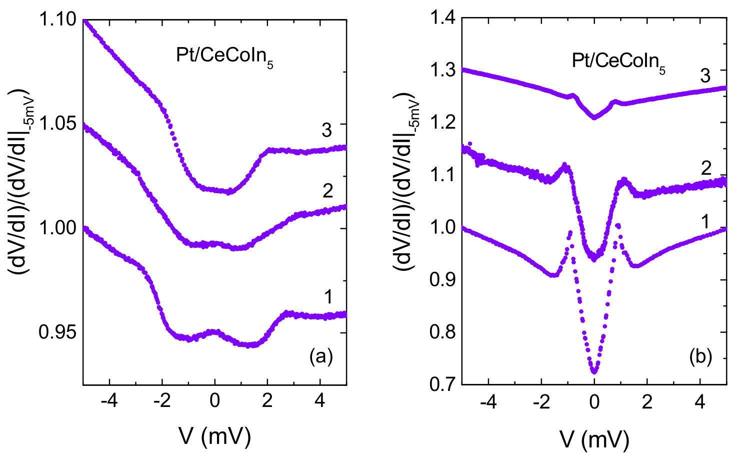


Fig. 1. Differential resistance $dV/dI$ *vs* voltage $V$ of point contacts between $CeCoIn_5$ and Pt at $T = 1.5$ K. The contact resistance is $R_0 = 3.3\,\Omega$ (1), $2.1\,\Omega$ (2), and $3.6\,\Omega$ (3) for curves in panel (a) and $R_0 = 4.2\,\Omega$ (1), $1.2\,\Omega$ (2), and $1.6\,\Omega$ (3)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

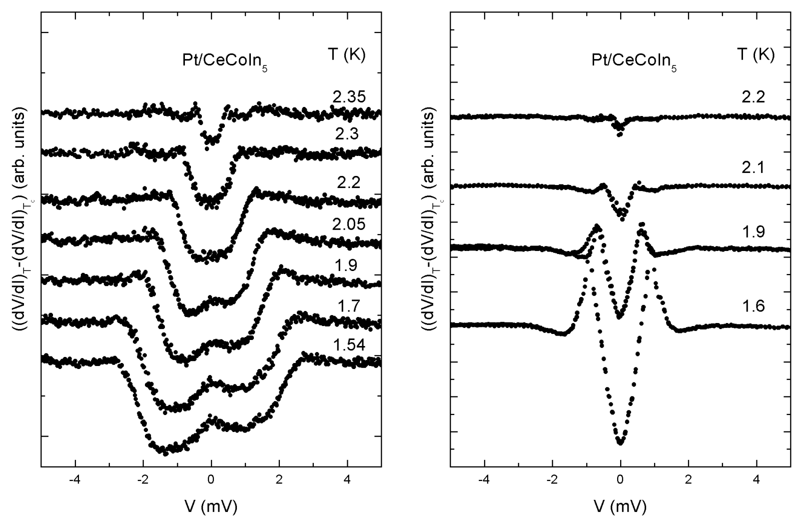


Fig. 2. Temperature dependence of both types of structures in the differential resistance $dV/dI$ *vs* $V$.

"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 $\Delta$ can be inferred by fitting the curves, although the exact value depends on the choice of the order parameter. A rough estimate shows that $\Delta$ is well above the weak-coupling limit $2\Delta = 3.5k_{\mathrm{B}}T_{\mathrm{c}} = 0.69\,\mathrm{meV}$.

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 $CeCoIn_5$ 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.

Research at UCSD was supported by the VS DOE and NSF.

## REFERENCES


[1] C. Petrovic *et al.*, *J. Phys.: Condens. Matter* **13**, L337 (2001).
[2] V.S. Zapf, *et al.*, *Phys. Rev.* **B**65, 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.* **B**64, 134526 (2001).
[6] G.E. Blonder, M. Tinkham, T.M. Klapwijk, *Phys. Rev.* **B**25, 4515 (1982).
[7] Chr. Bruder, *Phys. Rev.* **B**41, 4017 (1990).
[8] M. Fogelström *et al.*, *Phys. Rev. Lett.* **79**, 281 (1997).