# Microwave Conductivity and Penetration Depth in the Heavy Fermion Superconductor $CeCoIn_5$

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(Received 30 August 2001; published 14 January 2002)

The electrodynamic properties of the quasi-two-dimensional heavy fermion superconductor $CeCoIn_5$ have been investigated by microwave surface impedance measurements over a wide range of microwave frequencies and temperatures. We derive a value penetration depth $\lambda(0) \sim 190$ nm, with a strong linear term in the temperature dependence of $\lambda(T)$ below $T_c/3$, consistent with a superconducting gap with line nodes. The real part of the conductivity displays a broad peak at low temperatures consistent with a decreased scattering rate of almost 2 orders of magnitude below $T_c$. $CeCoIn_5$ has remarkably similar properties to those of the high-$T_c$ cuprates.

DOI: 10.1103/PhysRevLett.88.047005 PACS numbers: 74.25.Ha, 74.25.Nf, 74.70.Tx

The heavy fermion family of superconductors has recently been expanded by the discovery of the compounds $CeMIn_5$ (M = Co, Ir, Rh) [1,2]. $CeCoIn_5$ and $CeIrIn_5$ have superconducting transitions at 2.3 K and 400 mK at ambient pressure, while $CeRhIn_5$ orders antiferromagnetically at 3.8 K with superconductivity induced at 2.1 K by the application of 16 kbar of pressure. The crystal structure is tetragonal and is built of alternating layers of $CeIn_3$ (a heavy fermion antiferromagnet with pressure induced superconductivity [3]) and $MIn_2$. These materials provide the opportunity to study superconductivity in the vicinity of a magnetic instability and help expand our understanding of magnetically mediated superconductivity and its relevance to other strongly correlated electron systems.

Evidence for unconventional superconductivity in these Ce-based heavy fermion superconductors is mounting. Recent heat capacity, thermal conductivity measurements [4], and NMR relaxation rates [5,6] reveal power law temperature dependences at low temperatures. This has been interpreted as an indication of an unconventional superconductor with line nodes. Furthermore, $CeCoIn_5$ displays typical heavy fermion metallic behavior with a broad maximum in the resistivity close to 30 K associated with the crossover from incoherent Kondo scattering at higher temperatures to the formation of Bloch states made up of heavy electrons at lower temperatures, followed by a linear temperature dependence below 20 K. The linear temperature dependence is a common feature of magnetically mediated superconductors and is believed to be associated with proximity to a quantum critical point [3]. Recent de Haas–van Alphen measurements have demonstrated that $CeCoIn_5$ is a quasi-two-dimensional metal dominated by a cylindrical electron Fermi surface with large electron effective masses [7]. It is also a rather clean material, which grows as large platelike single crystals with almost optically flat surfaces. The superconducting temperature is the highest of any known heavy fermion metal at ambient pressure. This material therefore provides an excellent opportunity to investigate heavy fermion superconducting properties in a clean quasi-two-dimensional system.

In this Letter we report a comprehensive set of measurements of the complex surface impedance of a high quality, single crystal of $CeCoIn_5$ over a wide range of frequencies and temperatures. The electromagnetic properties are shown to be very similar to those of the high-$T_c$ cuprate superconductors.

The measurement of the surface impedance ($Z_s = R_s + iX_s$) has played a key role in expanding our understanding of superconductivity. This was emphasized by the measurement of a linear term in the low-temperature dependence of the in-plane microwave penetration depth of YBCO by Hardy *et al.* [8,9], which gave direct evidence for unconventional superconductivity with line nodes in the energy gap. Such measurements probe the complex conductivity ($\sigma = \sigma' - i\sigma''$) as a function of temperature and frequency, from which the superfluid density as well as the properties of the thermally excited quasiparticles can be deduced. In the local limit the surface impedance and complex conductivity are given by

$$Z_s = R_s + iX_s = \left(\frac{i\mu_0\omega}{\sigma' - i\sigma''}\right)^{1/2}, \tag{1}$$

where $R_s$ is the surface resistance and $X_s$ is the surface reactance. The two-fluid model gives a conductivity

$$\sigma = \left(\frac{ne^2}{m^*}\right)\left[\frac{f_s}{i\omega} + \frac{f_n\tau}{(1 + i\omega\tau)}\right], \tag{2}$$

where $f_s = 1 - f_n$ is the superfluid fraction, and $f_n$ is the normal fluid fraction; in the superconducting state, $\tau$ is the scattering lifetime of the thermally excited quasiparticles and $m^*$ is their effective mass.

Microwave measurements have been made using a series of hollow dielectric resonators [10] over the temperature range from 20 K down to ~0.2 K. The crystals were mounted on the end of a cylindrical 0.5-mm-diam sapphire rod centered along the axis of the hollow resonator. The sapphire rod acted as a thermal link to a copper-heater block, which was weakly thermally coupled either to a pumped $^3$He reservoir or to a simple adiabatic demagnetization stage, depending on the range of temperatures over which measurements were made. The resonator and enclosing copper cavity were thermally linked to the pumped liquid $^4$He bath at 1.4 K. To within our experimental accuracy, "zerofield" measurements were insensitive to the application of small fields $\pm 50$ G $\ll H_{c2}$ (5 T, see Ref. [1]).

Microwave measurements were made using the $TE_{01n}$ resonant modes of sapphire, rutile, and $LaAlO_3$ resonators with the resonant modes at $f_0 = 2.16$, 4.5, 8.5, 10.26, and 15.08 GHz. For all modes, the microwave magnetic field component at the sample position was parallel to the axis of the sapphire rod and perpendicular to the $c$ axis of the crystal. Microwave currents were therefore induced flowing in the $ab$ planes across the major flat faces and in the $c$ direction on the thin edge faces. Because the anisotropy of this material determined from the anisotropy of $H_{c2}$ is relatively small ($\gamma \sim 2$, see Ref. [1]), the measurements are largely dominated by the surface impedance on the $ab$ surfaces. This has been confirmed by experiments involving the splitting of the sample into two to create two additional edge surfaces with no difference being measured in the surface impedance within experimental uncertainty.

The surface resistance and changes in surface reactance of the crystal were deduced from the full-width at half-maximum $\Delta f_B$ and changes of $f_0$ of the dielectric resonator using the relation $\Delta f_B(T) - 2i\Delta f_0(T) = \Gamma_f(R_s + i\Delta X_s)$, where $\Gamma_f$ is the mode-specific filling factor of the sample [11,12]. $\Delta f_B$ was corrected for contributions from the host resonator using reference measurements in the absence of the sample. Long-term frequency drifts were corrected by regularly monitoring $f_0$ at a fixed temperature, typically 0.6 K for low-temperature measurements. The sensitivity and reproducibility within a single run, $\Delta f_B \sim \Delta f_0 \sim 100$ Hz, enable us to measure temperature dependences of small samples down to temperatures well below 1 K. To avoid corrections from sample heating, microwave input powers were typically <100 nW, though no evidence for any heating was observed at 10 times greater power levels. Narrow band amplifiers and software signal processing were used to enhance the signal-to-noise ratio.

The crystals were grown from an In flux by combining stoichiometric amounts of Ce and Co with excess In in an alumina crucible, following Ref. [1]. This produced large single crystals which were etched slightly with HCl after decanting of the flux. The crystal used in these experiments has dimensions $0.5 \times 1.2 \times 0.1$ mm$^3$ with optically smooth surfaces and a $T_c \sim 2.2$ K, determined independently from microwave and dc measurements.

Figure 1 shows $R_s(T)$ for a wide range of microwave frequencies. In the normal state the absolute values of $R_s$ are proportional to $\omega^{1/2}$ and assume the classical skin depth result with a measured dc resistivity of 3.8 $\mu\Omega$ cm at 2.5 K on a crystal from the same batch having the same $T_c$. This value is typical of measurements on similar crystals produced by other groups [1]. The inset of Fig. 1 shows the temperature dependence of the normal state resistivity up to 20 K derived from our microwave measurements which agrees very well with the dc measurements (solid line, the data has been scaled to match at $T_c$). Absolute values of the resistivity vary systematically between samples due to uncertainties in contact separation, typically $\pm 15\%$. We note the strong linear term in the temperature dependence reminiscent of optimally doped cuprates. Below $T_c$, $R_s$ drops monotonically to a residual value of $\sim 100$ $\mu\Omega$ at 2.16 GHz, increasing with frequency as $\omega^2$ though with a slightly weaker dependence at higher frequencies when $\omega\tau$ becomes significant.

The surface reactance is shown in Fig. 2. The zero of the reactance data assumes that $R_s(T) = X_s(T)$ above $T_c$ at all frequencies. This equality is illustrated in the inset of Fig. 2 for the 2 GHz data. This procedure enables us to evaluate $X_s(0) \equiv \lambda(0) \sim 1900 \pm 100$ Å for the $ab$ plane. The peak close to $T_c$ arises because of the 90° phase change in the normal and superconducting response for $\omega\tau \ll 1$. The initial reduction of $f_n$ leads to a first order reduction in screening from the quasiparticles but

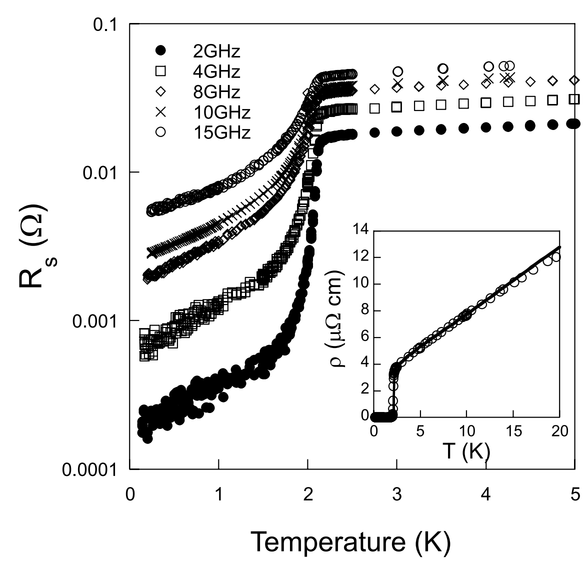


FIG. 1. Surface resistance at 2.16, 4.53, 8.54, 10.26, and 15.08 GHz of a high quality $CeCoIn_5$ single crystal. Inset: the open circles show the derived normal state resistivity obtained from the 2 GHz $R_s$ data compared to the measured dc resistivity, solid line. (The data have been scaled to match at $T_c$.)

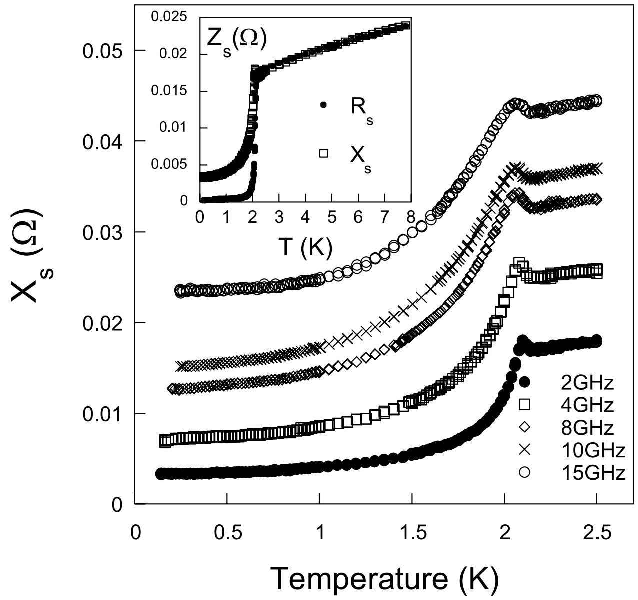


FIG. 2. The surface reactance. Note the peak close to $T_c$. Inset: $R_s$ and $X_s$ demonstrating the validity of $R_s = X_s$ over a wide temperature range.

only a second order increase in screening from the superfluid fraction. This leads to a peak that moves to lower temperatures on increasing frequency (see Fig. 2). An even more dramatic demonstration of this effect was recently reported for $Sr_2RuO_4$ [13–15], where the peak is even more pronounced due to the larger $\omega\tau$ values ($\omega\tau \sim 1$ at 10 GHz).

The temperature dependence of $\lambda(T)$ derived from $\sigma''(T)$ at 10 GHz is shown in Fig. 3. Within experimental errors, measurements at other frequencies fall on top of this curve. The main figure shows the low-temperature region, where $\lambda(T) \sim T$ below 0.8 K with a slope of 370 Å/K. Shown in Fig. 4 is $f_s = \lambda^2(0)/\lambda^2(T)$, obtained from $\sigma''$. Within the experimental uncertainty we obtain a linear temperature dependence for the superfluid density between 0.3 and 0.8 K. The overall shape of $f_s$ depends on the value of $\lambda(0)$ assumed, but does alter the linear temperature dependence below 0.8 K significantly. For a cylindrical Fermi surface, $f_s \propto T$ is consistent with a $d$-wave pairing state with line nodes [16] or a highly anisotropic $s$-wave state [17].

At the lowest temperatures there are indications of slight curvature in $\lambda(T)$, which could arise from several factors. A small amount of impurity can change $\lambda(T) \sim T$ to $T^2$ as observed by Bonn *et al.* [18] in measurements on $YBa_2Cu_3O_{6.95}$. We note that impurity scattering may well be significant in our crystal, as its $T_c$ (2.17 K) is slightly lower than the reported optimum (2.3 K). A quadratic temperature dependence can also arise from a crossover to nonlocal electrodynamics at low temperatures [19]. The situation will become clearer when the measurements are extended to lower temperatures and to purer samples.

The $f_s$ data is consistent with recent heat capacity measurements [4], which exhibit a linear temperature dependence of $C(T)/T$ for temperatures well below $T_c$ implying the existence of line nodes in the superconducting gap. Recent measurements of the dependence of thermal conductivity on field direction by Izawa *et al.* [20] are also consistent with the superconducting gap having $d_{x^2-y^2}$ symmetry with line nodes consistent with our measurements.

$\sigma'$ was extracted from $R_s$ and $X_s$ and is shown in Fig. 5. On cooling below $T_c$, $\sigma'$ initially increases monotonically with a rather broad peak at the higher frequencies. A very similar temperature and frequency dependence of $\sigma'(T)$ is observed for the cuprate superconductors [18].

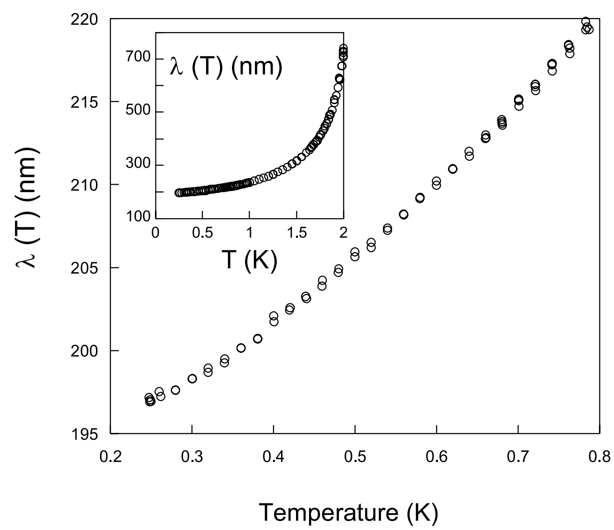


FIG. 3. The change in penetration depth displaying a strong linear term below 0.8 K. Inset: $\Delta\lambda$ over a wider temperature range.

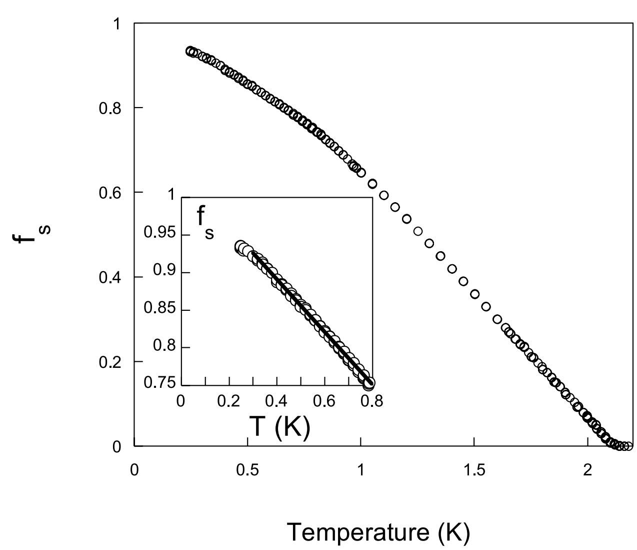


FIG. 4. The superfluid density $f_s(T)$ calculated for $\lambda(0) =$ 1900 Å. Inset: a closeup of the low-temperature region.

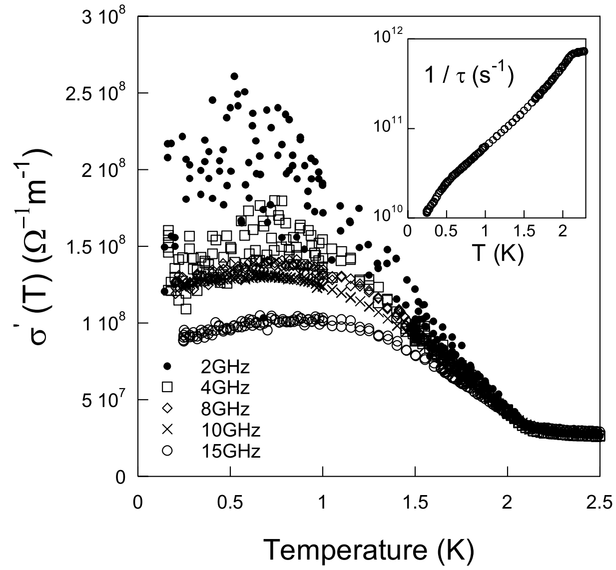


FIG. 5. The real part of the conductivity $\sigma'$. Inset: the scattering rate obtained using the two-fluid model.

Measurements at all frequencies can be described by the two-fluid model [Eq. (2)] using the value of $f_s = 1 - f_n$ derived from $\sigma''$ and a strongly temperature dependent quasiparticle relaxation rate varying as shown in the inset of Fig. 5.

Our measurements show that $1/\tau$ is frequency independent and drops by almost 2 orders of magnitude below $T_c$ (note that only the 10 GHz data are shown for clarity). The scattering rate varies as $\sim T^4$ in the temperature range 1.5 to 2 K, which is almost identical to that observed by Bonn *et al.* in their measurements on YBCO [18]. Below 1.5 K the temperature dependence of $1/\tau$ weakens and is almost linear below 0.8 K. A rapid temperature dependence of the scattering rate is expected when inelastic scattering originates from interactions that become gapped below $T_c$. A model based on quasiparticle lifetimes limited by spin-fluctuation scattering has been proposed by Quinlan *et al.* [21]. This model considers superconductors with both $s$-wave and $d_{x^2-y^2}$ symmetry. In the $d_{x^2-y^2}$ symmetry case, when a gap opens up in the spin wave spectrum, Quinlan *et al.* predict a scattering rate varying as $T^3$ at the lowest temperatures with an increasing power law dependence on approaching $T_c$. In our measurements we see a much weaker dependence at the lowest temperatures. A weaker temperature dependence was also observed in $YBa_2Cu_3O_{7-\delta}$ [9].

In summary, we present the first detailed measurements of the microwave surface impedance of a newly discovered, clean quasi-two-dimensional heavy fermion superconductor $CeCoIn_5$. We derive a value for $\lambda_{ab}(0) = 1900 \pm 100$ Å and observe a linear low-temperature dependence consistent with line nodes in the superconducting order parameter. In addition we determine the quasiparticle conductance from which we are able to extract the quasiparticle relaxation rate varying as $T^4$ close to $T_c$, suggestive of interactions with spin fluctuations. The observed microwave properties are very similar to those of the cuprate high-$T_c$ superconductors.

We are grateful to D. Brewster and G. Walsh for technical support. The research at Birmingham has been funded by the EPSRC of the United Kingdom.

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