OPTICAL CONDUCTIVITY OF Nd$_{1.85}$Ce$_{0.15}$CuO$_4$: STRENGTH OF THE CONDENSATE

C. C. HOMES$^*$, J. L. PENG$^b$, R. L. GREENE$^b$ and B. P. CLAYMAN$^c$

$^a$Department of Physics, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
$^b$Center for Superconductivity Research, Department of Physics and Astronomy, University of Maryland, College Park, MD 20742, USA
$^c$Department of Physics, Simon Fraser University, Burnaby, B.C., Canada V5A 1S6

Abstract—The $ab$-plane reflectance of a Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ single crystal ($T_c$ = 23 K) has been measured from $\approx$ 30 to 9500 cm$^{-1}$ above and below $T_c$, and the optical properties calculated from a Kramers–Kronig analysis. A rich phonon spectrum is observed with some new spectral features appearing below $\approx$ 100 K. The normal-state optical conductivity may be described by a Drude-like component and an overdamped mid infrared component. Below $T_c$, the plasma frequency of the condensate is $\omega_p \approx$ 10,000 cm$^{-1}$. The London penetration depth is determined to be $\lambda_L \approx$ 1600 ± 100 Å, which places it well off the Uemura line. Estimates of the electron–phonon coupling from normal-state transport measurements yield $\lambda_e < 0.5$. The small values for the penetration depth and the electron–phonon coupling constant suggest that the superconductivity in this material is not due to the electron–phonon mechanism, and is different to that in other hole-doped superconducting cuprates. © 1998 Elsevier Science Ltd. All rights reserved

In most high-temperature (high-$T_c$) superconducting cuprates, such as YBa$_2$Cu$_3$O$_{7-\delta}$ and La$_{2-x}$Sr$_x$CuO$_4$, the charge carriers are doped holes. However, in Nd$_{2-x}$Ce$_x$CuO$_4$, where superconductivity is induced by substituting Nd$^{3+}$ with Ce$^{4+}$, the CuO$_2$ planes are believed to be doped with electrons [1, 2] as well as holes [3].

The Nd$_{2-x}$Ce$_x$CuO$_4$ system has attracted a great deal of interest because of its possible conventional BCS $s$-wave pairing in the superconducting state, as opposed to the unconventional $d$-wave behavior proposed for the hole-doped cuprates [4, 5]. The microwave surface impedance measurements on both thin films and single crystals have shown evidence for a conventional BCS $s$-wave behavior with a gap of $2\Delta$ = 4k$_B$T$_c$ [6–8]. Tunneling measurements have also shown a resemblance to conventional superconductors [9]. However, the magnetic field dependence of the specific heat anomaly [10, 11] and thin film transmission [12] of Nd$_{2-x}$Ce$_x$CuO$_4$ both show a non-BCS-like behavior.

Whether or not this system can be considered as a conventional BCS-type superconductor is an important question, given the strong evidence that the other hole-doped cuprates are not. The optical properties of materials in the normal and superconducting states can provide a wealth of information about the electron-dynamics of the system, and can yield important information about the nature of the superconductivity.

Large, single crystals of Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ were grown from a CuO-based flux using a directional solidification technique [13]. During the course of the growth, the flux was allowed to flow out of the crucible at the end of the growth process, so that free-standing crystals are left in the bottom of the crucible that do not need to be mechanically separated from the flux. To induce superconductivity, the crystals were annealed in an inert gas atmosphere. Both resistivity and magnetization showed a sharp superconducting transition at 23 K, with a width of $< 1$ K [13].

The reflectance of a single crystal of Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ has been measured for the radiation polarized parallel to the $a$–$b$ plane from $\approx$ 30 to 9500 cm$^{-1}$ at temperatures above and below $T_c$. A Bruker IFS113v Fourier transform interferometer, using a sensitive overfilling technique [14]. The crystal examined in this case was $\approx$ 2 × 2 mm in the $a$–$b$ plane, and had a flat, mirror-like surface that was free of flux. The optical properties (i.e. the complex conductivity $\sigma = \sigma_1 + i\sigma_2$) have been calculated from a Kramers–Kronig analysis of the reflectance. At low frequency, the reflectance was extrapolated to zero frequency by assuming a Hagens–Rubens $1 - R \propto \sqrt{\omega}$ dependence above $T_c$, and a superconducting $1 - R \propto \omega^4$ dependence below $T_c$. The reflectance has been extended to $\approx$ 35 eV using data from related materials [15, 16], above which a free-electron ($R \propto \omega^{-2}$) behavior was assumed.

The reflectance of Nd$_{1.85}$Ce$_{0.15}$CuO$_4$ is shown in Fig. 1(a) from $\approx$ 30 to 1000 cm$^{-1}$ in the normal state and below $T_c$. The optical conductivity has been determined from a Kramers–Kronig analysis of the reflectance and is shown in Fig. 1(b) for the same temperatures over
observed below the delta function at zero frequency. The strength of the transfer of spectral weight from the free carriers into the same frequency range. The free-carrier component which may be characterized as a Lorentzian centered at zero frequency of the condensate, \( \omega_{pS} = 10,000 \text{ cm}^{-1} \) [17]. The penetration depth is also related to the plasma frequency of the condensate, \( 1/\delta(T) = 2\pi\omega_{pS}(T) \), giving \( \lambda_{ab} = 1600 \, \text{Å} \) at 10 K.

It has been noted that in many of the cuprate-based high temperature superconductors \( \delta \propto T_c \) [18], which is shown in Fig. 2 for a variety of materials. However, the value of \( \delta \) for Nd\(_{1.85}\)Ce\(_{0.15}\)CuO\(_4\) is much larger than the low \( T_c \) for this system would suggest, indicating that this material is not like other cuprate superconductors.

An examination of the conductivity in Fig. 1(b) below \( T_c \) indicates that the large errors associated with the conductivity at low frequency (assuming an error of \( \pm 0.1\% \) in the reflectance) precludes an unambiguous determination of the nature of the energy gap in this system. However, the low value of the electron–phonon coupling constant \( \lambda_e \) determined from transport measurements [19], and the absence of any phonon anomalies due to a Holstein mechanism [20] at or below \( T_c \), suggests that while a BCS-type mechanism may not be ruled out, the superconductivity in this material is probably not phonon mediated.

In summary, the strength of the condensate in Nd\(_{1.85}\)Ce\(_{0.15}\)CuO\(_4\) has been calculated from the optical properties. The large value for \( \omega_{pS} \) (and small value of \( \lambda_e \)) is suggestive of a 90 K superconductor, rather than the observed \( T_c \approx 23 \, \text{K} \). This result, when coupled with the small value of \( \lambda_{ab} \) and the absence of any phonon anomalies at \( T_c \) indicates that superconductivity of this

Both methods yield \( \omega_{pS} = 10,000 \, \text{cm}^{-1} \) [17]. The penetration depth is also related to the plasma frequency of the condensate, \( 1/\delta(T) = 2\pi\omega_{pS}(T) \), giving \( \lambda_{ab} = 1600 \, \text{Å} \) at 10 K.

It has been noted that in many of the cuprate-based high temperature superconductors \( \delta \propto T_c \) [18], which is shown in Fig. 2 for a variety of materials. However, the value of \( \delta \) for Nd\(_{1.85}\)Ce\(_{0.15}\)CuO\(_4\) is much larger than the low \( T_c \) for this system would suggest, indicating that this material is not like other cuprate superconductors.

An examination of the conductivity in Fig. 1(b) below \( T_c \) indicates that the large errors associated with the conductivity at low frequency (assuming an error of \( \pm 0.1\% \) in the reflectance) precludes an unambiguous determination of the nature of the energy gap in this system. However, the low value of the electron–phonon coupling constant \( \lambda_e \) determined from transport measurements [19], and the absence of any phonon anomalies due to a Holstein mechanism [20] at or below \( T_c \), suggests that while a BCS-type mechanism may not be ruled out, the superconductivity in this material is probably not phonon mediated.

In summary, the strength of the condensate in Nd\(_{1.85}\)Ce\(_{0.15}\)CuO\(_4\) has been calculated from the optical properties. The large value for \( \omega_{pS} \) (and small value of \( \lambda_e \)) is suggestive of a 90 K superconductor, rather than the observed \( T_c \approx 23 \, \text{K} \). This result, when coupled with the small value of \( \lambda_{ab} \) and the absence of any phonon anomalies at \( T_c \) indicates that superconductivity of this

Both methods yield \( \omega_{pS} = 10,000 \, \text{cm}^{-1} \) [17]. The penetration depth is also related to the plasma frequency of the condensate, \( 1/\delta(T) = 2\pi\omega_{pS}(T) \), giving \( \lambda_{ab} = 1600 \, \text{Å} \) at 10 K.

It has been noted that in many of the cuprate-based high temperature superconductors \( \delta \propto T_c \) [18], which is shown in Fig. 2 for a variety of materials. However, the value of \( \delta \) for Nd\(_{1.85}\)Ce\(_{0.15}\)CuO\(_4\) is much larger than the low \( T_c \) for this system would suggest, indicating that this material is not like other cuprate superconductors.

An examination of the conductivity in Fig. 1(b) below \( T_c \) indicates that the large errors associated with the conductivity at low frequency (assuming an error of \( \pm 0.1\% \) in the reflectance) precludes an unambiguous determination of the nature of the energy gap in this system. However, the low value of the electron–phonon coupling constant \( \lambda_e \) determined from transport measurements [19], and the absence of any phonon anomalies due to a Holstein mechanism [20] at or below \( T_c \), suggests that while a BCS-type mechanism may not be ruled out, the superconductivity in this material is probably not phonon mediated.

In summary, the strength of the condensate in Nd\(_{1.85}\)Ce\(_{0.15}\)CuO\(_4\) has been calculated from the optical properties. The large value for \( \omega_{pS} \) (and small value of \( \lambda_e \)) is suggestive of a 90 K superconductor, rather than the observed \( T_c \approx 23 \, \text{K} \). This result, when coupled with the small value of \( \lambda_{ab} \) and the absence of any phonon anomalies at \( T_c \) indicates that superconductivity of this
material is probably not phonon mediated, yet it is also unlike other cuprate superconductors.

Acknowledgements—This work was supported by the Natural Sciences and Engineering Research Council of Canada. The authors would also like to acknowledge many useful discussions with D. N. Basov and T. Timusk.

REFERENCES