Direct Measurement of the Temperature-Dependent Magnetic Penetration Depth in Y-Ba-Cu-O Crystals

L. Krusin-Elbaum, R. L. Greene, F. Holtzberg, A. P. Malozemoff, and Y. Yeshurun[a]
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598-0218
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The temperature dependence of the magnetic penetration depth λ is determined directly from low-field dc magnetization measurements on single-crystal Y-Ba-Cu-O (T_c=89.7 K, ΔT_c=0.2 K). The results are consistent with the behavior expected from a BCS (*s* wave) superconductor.

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One of the basic lengths of superconductivity is the magnetic penetration depth λ. The temperature dependence of λ, since it depends explicitly on the superconducting energy gap,[1] is related fundamentally to the symmetry of the superconducting state, and thus to the mechanism of pairing. Furthermore, the zero-temperature value λ(0) contains information on the effective mass and the density of the superconducting carriers. There are many reports[2] on the magnitude and temperature dependence of λ in unoriented samples of Y-Ba-Cu-O, obtained by a variety of techniques.[3-13] These measurements have given conflicting results both for λ(*T*) and for λ(0). Some of the experiments are consistent with conventional BCS theory which has a superconducting gap over the entire Fermi surface, while other experiments suggest an unconventional pairing mechanism in which the gap is zero on portions of the Fermi surface. In addition, there are two recent measurements of λ(*T*) in *c*-axis–oriented but polycrystalline films[14,15] which also give conflicting results. The probable cause of such significant disagreement among prior measurements is the polycrystalline nature of the samples. Factors such as different preparation conditions, averaging of anisotropic properties, uncertainties about local demagnetizing factors, and surface and grain boundary effects (e.g., Josephson coupling between grains) make an accurate measurement of λ(*T*) exceedingly difficult.

In this Letter we report a *direct* measurement of the temperature-dependent penetration depth in high-quality *single crystals* of Y-Ba-Cu-O using a *low-field* dc magnetization technique. The temperature dependence of λ extracted from our data is entirely consistent with BCS (*s* wave) pairing with a low-temperature value of the penetration depth of about 1400 Å for the field penetration perpendicular to the *a-b* plane. We argue that our single-crystal results represent the intrinsic behavior of λ(*T*) in Y-Ba-Cu-O.

dc magnetization versus temperature measurements, *M*(*T*), have been performed on thin platelike crystals, grown by a technique described previously.[16] The sizes of the crystals varied significantly, with the thickness along the *c*-axis ranging from 20 to 80 μm. The measurements were performed in a noncommercial SQUID magnetometer described elsewhere.[17] The measurement procedure is first to cool the crystals to 4.2 K in "zero field" (the background field of 0.5 mOe). Zero-field-cooled (ZFC) curves, such as shown in Figs. 1 and 2, are obtained on slow warmup after a small field (typically around 1 Oe) is turned on. In this experiment the applied field is in the *a-b* plane (see inset to Fig. 1), a geometry which gives a negligible demagnetization correction and which allows for a very simple relationship between magnetic susceptibility χ and λ.[18] The ZFC data are completely reversible (within the noise level of 5 parts in 10^4 and within the time scale of this measurement, which is typically ~15 h) up to at least 88 K. This observation is essential, since lack of reversibility would imply the existence of surface barriers or flux trapping, both of which would obscure the change in magnetization due to the intrinsic temperature variation of λ. In all crystals we consistently observe a very sharp (less than 0.5 K at 1 Oe)

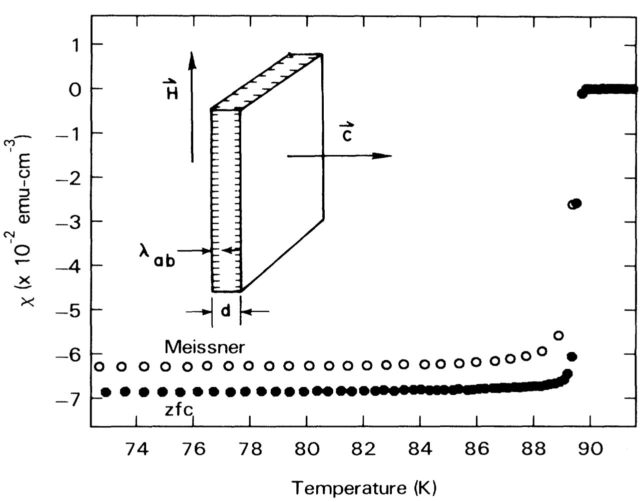

FIG. 1. ZFC and field-cooled (Meissner) magnetizations of Y-Ba-Cu-O crystal as functions of temperature. The field of 1 Oe is applied parallel to the *a-b* plane. The superconducting transition with onset at 90 K is very sharp (ΔT_c=200 mK). Inset: The topology of the experiment, where the relevant magnetic penetration depth is indicated.

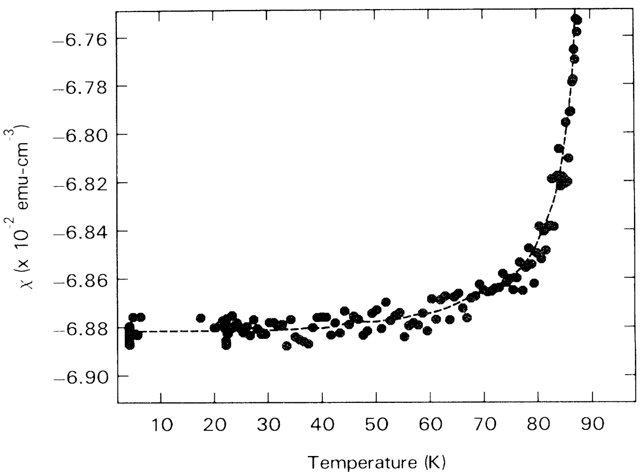

FIG. 2. ZFC magnetization of Fig. 1 at low temperatures for the same field. The vertical scale is expanded to indicate the signal-to-noise ratio in our measurements. Dashed line represents a guide to the eye.

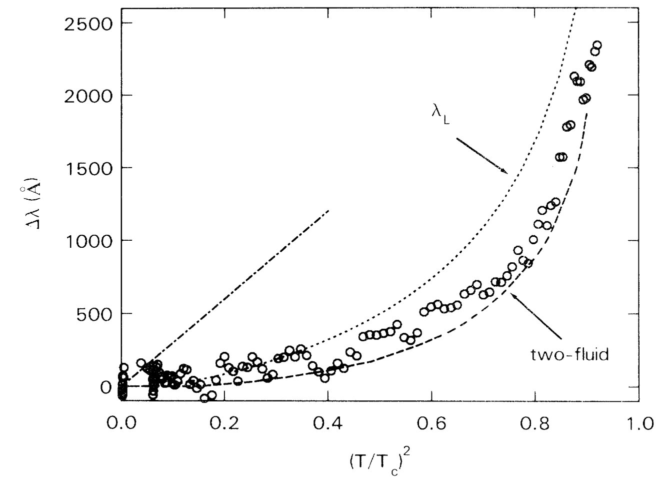

FIG. 3. The change in the magnetic penetration depth calculated with use of Eq. (1), as a function of reduced temperature. Dashed line is a two-fluid approximation with $\lambda(0)=1400$ Å and dotted line represents the clean weak-coupling penetration depth λ_L for $\lambda(0)=1400$ Å (calculated from Ref. 21). λ_L also fits the data if $\lambda(0)\simeq 900$ Å. The dot-dashed line is the behavior seen in some polycrystalline samples and films (see text for discussion).

superconducting transition in the ZFC data at temperatures around 90 K pointing to the high quality of the crystals used in this study. The surfaces appear smooth and clean under $\times 50$ optical magnification. The reversible ZFC data, which are in thermodynamic equilibrium for $H < H_{c1}$ are used to determine $\lambda(T)$.

The large (80% of $1/4\pi$) flux expulsion[19] (Meissner effect) which is recorded on cooling in the same magnetic field through the critical temperature is also reversible up to the comparable temperatures. We find slightly larger changes in the Meissner data, which we believe reflect reversible motion of flux in and out of the crystal and thus do not represent the intrinsic field penetration at the sample surface.

The ZFC magnetization in Fig. 1 is that of a single crystal having dimensions $1346\times 1734\times 43$ μm^3, the smallest dimension being along the c axis. The field is applied in the direction perpendicular to the c axis, i.e., along the twinned a-b plane. An expansion of the data is shown in Fig. 2 which also indicates the signal-to-noise ratio of our experiment. The applied field here is 1 Oe, which should be contrasted with the muon-spin-rotation measurements[3] where the applied field is orders of magnitude higher. In our direct technique, the low applied field is desirable, so that any variation in magnetization from flux penetration of nonintrinsic origin, such as rough surfaces and edge effects, is minimized.

The expression for the susceptibility of a superconducting thin plate in the geometry of our experiment is given by[18]

$$\frac{\chi}{\chi_0}=1-\frac{2\lambda}{d}\tanh\left[\frac{d}{2\lambda}\right], \tag{1}$$

where d is the plate thickness and χ_0 is the zero-temperature value of the magnetic susceptibility M/H, with the applied field H corrected for the demagnetization.[20] For our crystals we expect λ to be much smaller than d, so that Eq. (1) can be well approximated by $\chi/\chi_0=1-2\lambda/d$, where λ is λ_{ab} as shown in the inset to Fig. 1. The subscript ab here refers to the fact that the shielding currents are flowing in the a-b plane. The change of λ from its low-temperature value can then be determined from the variation of susceptibility with temperature, i.e., $\Delta\chi/\chi_0=2\Delta\lambda/d$.

The change in the penetration depth obtained with use of Eq. (1) is shown in Fig. 3 where it is compared with two theoretical predictions: the empirical two-fluid relation[1]

$$\frac{\lambda(T)}{\lambda(0)}=\left[1-\left(\frac{T}{T_c}\right)^4\right]^{-1/2}\equiv y\,, \tag{2}$$

and the penetration depth (labeled λ_L) calculated from weak-coupling BCS theory ($2\Delta=3.5kT_c$) in the local limit.[21] As pointed out by Rammer,[22] the two-fluid relation closely follows the penetration depth for a strong-coupled BCS superconductor. The calculation of λ_L assumes local electrodynamics ($\lambda\gg$ the mean-free-path-corrected coherence length[1]), which is the appropriate limit for the high-T_c superconductors.[2] To estimate $\lambda(0)$ we use Eq. (2) with the midpoint $T_c=89.5$ K and plot $\Delta\lambda$ against y as shown in Fig. 4. Near T_c (large y), the straight-line dependence is that expected from the two-fluid relation [Eq. (2)] and the slope gives us an estimate of $\lambda_{ab}(0)\simeq 1400$ Å. In the geometry of our experi-

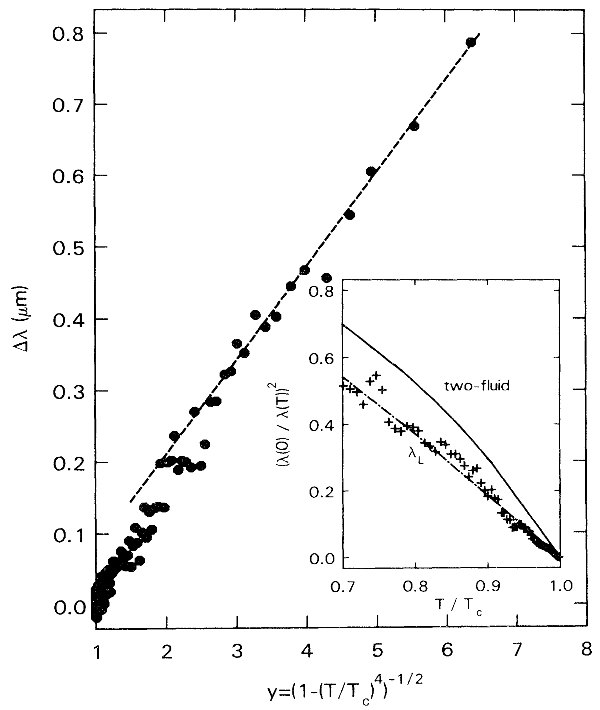

FIG. 4. The change in the magnetic penetration depth as a function of two-fluid parameter y. This representation of the data emphasizes the regime near T_c. From the linear slope of $\Delta\lambda$ vs y we extract $\lambda(0)=1400\pm 50$ Å. Inset: The same data compared to the calculated λ_L taking $\lambda(0)$ as 900 Å.

ment this λ corresponds to field penetration perpendicular to the a-b plane. This value is in excellent agreement with an estimate of $\lambda_{ab}(0)$ obtained from a measurement of H_{c1} (Ref. 20) in single crystals and by neutron scattering from an oriented film.[13] It should be pointed out that an accurate determination of $\lambda_{ab}(0)$ cannot be made without knowledge of the exact functional form of $\lambda(T)$, which depends on parameters such as the coupling strength and the mean free path.[22] For instance the weak-coupling λ_L curve shown in Fig. 3 could also fit our data if we take $\lambda_{ab}(0)$ equal to 900 Å (see inset to Fig. 4). The slope of λ vs y in Fig. 4 is sensitive to the choice of T_c. Our choice of the midpoint seems most reasonable, but choosing the onset for T_c would yield a value of $\lambda(0)\simeq 1900$ Å in the two-fluid fit and a value $\lambda(0)\simeq 1400$ Å in the λ_L fit. These uncertainties bound the estimate of $\lambda_{ab}(0)$ from our data to 1400 ± 500 Å within extreme limits of $\lambda(T)$ given by BCS theory. The value of the penetration depth λ_c is not easily determined in our experiment, since it makes a negligible contribution to $\Delta\chi$ because of the sample geometry. From measurements of the anisotropy of H_{c1},[20] $\lambda_c(0)$ is about 3 times larger than $\lambda_{ab}(0)$.

The low-temperature $(T/T_c<0.5)$ variation in $\lambda(T)$ is particularly sensitive to the pairing mechanism. A power-law temperature dependence will result if the energy gap vanishes somewhere on the Fermi surface. This behavior has been observed in the heavy-fermion superconductors[23] and has been attributed to a nonconventional pairing mechanism. On the other hand, an anisotropic gap without nodes will always give a low-temperature exponential behavior characterized by the minimum value of the gap and lead to a temperature dependence close to the calculated λ_L shown in Fig. 3.

As seen in Fig. 3 our low-temperature data are consistent with $\lambda_L(T)$ calculated from BCS theory. Many of the prior measurements on polycrystalline samples found a power-law dependence for λ with magnitude well above the scatter of our data. In some of our crystals we also found[24] a T^2 dependence for λ, similar in magnitude to that found in some polycrystalline samples[4,5,8] and in c-axis-oriented films.[10,14] This is the dot-dashed line in Fig. 3. We have no definitive explanation for these low-T deviations; however, there are certainly many nonintrinsic origins for flux leakage into a sample which would give an apparent increase in λ and possibly a non-BCS temperature dependence. These include rough surfaces, inhomogeneous oxygen distribution, edge effects, and grain boundary effects. Since the data presented here (and found in another crystal) show the *smallest* change in λ at low temperatures, we conclude this to be the intrinsic behavior for the penetration depth in Y-Ba-Cu-O. The temperature dependence shown in Fig. 3 is in agreement, within experimental error, with that expected for conventional singlet (s wave) pairing.

The absolute value of $\lambda_{ab}(0)$ can be used to estimate other quantities of fundamental interest if we assume the conventional London formula

$$\lambda(0)=[m^*c^2/4\pi ne^2]^{1/2}, \tag{3}$$

where n is the normal-state carrier density and m^* is the effective mass of the carriers. Taking the value of $\lambda(0)$ to be 1400 Å and $n\simeq 5\times 10^{21}$ carriers cm^{-3}, taken from a direct chemical measurement,[25] we find $m^*\simeq 4m_e$. This estimate of m^* is consistent with the value determined from infrared reflectivity measurements[26] from the a-b plane of crystals similar to those used in our experiment. The origin of this enhancement is not yet determined but if it results from the same interaction responsible for the superconductivity in Y-Ba-Cu-O, then this interaction is in the strong-coupling limit. However, other measurements[15,20] point toward weak coupling, and our present data cannot distinguish between these possibilities without an independent determination of $\lambda(0)$. We should remark that our estimate of m^* is oversimplified since the nature of the states at the Fermi surface in Y-Ba-Cu-O is unknown.

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[a]Permanent address: Department of Physics, Bar-Ilan University, Ramat-Gan, Israel.

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