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Temperature dependence of the magnetic penetration depth in the high-T_c superconductor $Ba_2YCu_3O_{9-\delta}$: Evidence for conventional s-wave pairing

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Transverse-field muon-spin-relaxation (μSR) measurements have been performed on $Ba_2YCu_3O_{9-\delta}$ ($\delta = 2.1 \pm 0.05$) above and below its superconducting transition temperature. The temperature dependence of the magnetic penetration depth, deduced from the μSR data, is that of an ordinary s-wave (not d-wave with nodes in the gap function) superconductor. The data at 6 K indicate a magnetic penetration depth of $\lambda \approx 1400$ Å which, in the limit of extreme anisotropy, reduces to $\lambda \approx 1065$ Å.

Over the last several months, various compounds containing copper oxides have been found to be superconducting with transition temperatures (T_c's) several times larger than that of Nb_3Ge. Indeed, very recently, T_c's of the order of 90 K were found in a mixed-phase sample with optimal formulation $Y_{1.2}Ba_{0.8}CuO_{4-y}$.[1] Another study[2] demonstrated that the pure superconducting component in this mixture is the perovskite-type compound $Ba_2YCu_3O_{9-\delta}$ ($\delta = 2.1 \pm 0.05$). In the present paper, we describe the first measurements of the temperature-dependent magnetic penetration depth and flux-pinning effects in $Ba_2YCu_3O_{9-\delta}$. As in an earlier study[3] of $La_{1.85}Sr_{0.15}CuO_4$, we have used the muon-spin-relaxation (μSR) technique because its results are relatively simple to interpret and the experiments are readily performed on bulk samples.

The sample is a sintered disk, roughly 2.5 cm in diameter and 3 mm thick. It was prepared one day prior to the experiment using procedures described previously,[2] and exhibits a resistive transition at 90 K, and a complete Meissner effect for $H_{ext} = 100$ Oe and $T < 70$ K. The μSR experiments were performed on the M15 secondary channel of the TRIUMF cyclotron facility. The time-differential technique used in this study is described elsewhere[4] so only a brief discussion will be given here. Positive muons (4.2 MeV) are stopped in the sample where they decay, emitting a positron preferentially along their final spin polarization. A clock is started when the incident muon enters the sample and stopped upon the subsequent detection of the decay positron. Because the muons are created (via pion decay) with spin antiparallel to their momentum, the time evolution of the muon spin can be observed. Typically, one measures the spins of millions of muons (one at a time), yielding an ensemble average. Standard magnetic-field geometries allow the application of fields in directions parallel (longitudinal) or perpendicular (transverse) to the initial muon polarization. In the present work, only transverse field measurements were made, yielding a T_2-type relaxation function $G_{xx}(t)$ consisting of a relaxation envelope modulating a precessing muon asymmetry. Because this technique allows only one muon in the sample at a time, there are no complications due to μ^+-μ^+ interactions.

The muon depolarization rate $\Lambda(T)$, which is proportional to the width of the internal field distribution, was obtained at each temperature from Gaussian fits of the muon precession decay envelope. We emphasize that Gaussian fits were used because they provide a convenient method for measuring the mean-square fluctuations in the internal field; the second moment of the internal field dis-

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tribution is the only quantity of interest in this paper. Higher-statistics measurements are planned to determine higher-order moments of the internal field distribution and, concomitantly, deviations from the Gaussian form. The temperature dependence of Λ is shown in Fig. 1(a). The data shown were taken as a function of decreasing temperature in an external field (H_{ext}) of 3.4 kG. Data were also taken as a function of increasing temperature after field cooling, indicating no thermal hysteresis. Note that the critical temperature measured by μSR ($T_c=80$ K), where $\Lambda(T)$ begins to increase, corresponds to the midpoint of the rise in the dc magnetization, shown in Fig. 1(b), measured on a segment of the same sample by a SQUID magnetometer. The apparent difference of a few degrees in the onset temperatures measured by the two techniques is not too surprising since the muons sample the fields inside the individual grains (for $H_{\text{ext}} \gg H_{c1}$), whereas the magnetization reflects the flux expulsion, which might imply a slightly higher T_c for the grain surfaces (for $H_{\text{ext}} < H_{c1}$). Above 80 K, the fitted Λ, which is entirely due to interactions with static nuclear dipoles, is relatively small ($\sim 0.1\ \mu s^{-1}$); below 80 K, however, Λ increases sharply. This effect is characteristic of type-II superconductors where vortex lattices form to allow external field penetration.[5] The resulting inhomogeneities in the internal field lead to a line broadening in magnetic resonance or an enhanced spin-relaxation rate in μSR. For the square Abrikosov lattice, the mean-square field inhomogeneity in the mixed state (i.e., $H_{c1} < H_{\text{ext}} < H_{c2}$) is[6]

$$\langle |\Delta H|^2 \rangle = H_{\text{ext}} \frac{\phi}{4\pi\lambda^2} \left[1 + \frac{4\pi^2\lambda^2 H_{\text{ext}}}{\phi} \right]^{-1} = 2\frac{\Lambda^2}{\gamma_\mu^2} , \qquad (1)$$

where γ_μ ($=2\pi \times 13.55$ MHz/kG) is the muon gyromagnetic ratio, λ the magnetic penetration depth, and $\phi = hc/e^*$ is the magnetic flux quantum appropriate to the superconducting state of interest. It has also been shown[6] that the corrections to Eq. (1) for a triangular flux lattice are negligible. Since $e^* = 2e$,[7] as for ordinary BCS superconductors, we obtain $\lambda \approx 1400$ Å at 6 K from our data. If one accounts for an extreme anisotropy, one obtains a reduced value of $\lambda \approx 1065$ Å, which is almost identical to the updated[2] value of ~ 1000 Å obtained from extrapolations of bulk measurements of H_{c1} and H_{c2}.

Directly measured or derived values of the Sommerfeld constant γ vary somewhat,[2] making any further calculations of other parameters subject to uncertainty. As well, a major shortcoming of all of these estimates is the assumption of a single spherical Fermi surface. Bearing this in mind, one can combine our value of λ(≈ 1400 Å) with the Sommerfeld constant [assume $\lambda = 9$ mJ/(mole-Cu K^{-2})], to obtain a normal-state carrier density $n = 1.0 \times 10^{22}$ cm^{-3} and an effective carrier mass (m^*) of about seven free electron masses (m_e). The value of n obtained corresponds to nearly two carriers per chemical unit cell or $\frac{2}{3}$ of a carrier per Cu atom. For comparison, $La_{1.85}Sr_{0.15}CuO_4$, λ ($T=6$ K) was found to be 2500 Å, and a similar analysis yielded a lower charge carrier density ($n = 0.3 \times 10^{22}$ cm^{-3}) as well as a slightly lower effective-mass ratio $m^*/m_e \approx 6$. Dirty limit corrections amount to $\sim$10%–20%, since the mean free path is approximately equal to the Landau-Ginzburg coherence length (ξ).[2,8]

For an ordinary superconductor (i.e., a nonlocal BCS superconductor with an approximately isotropic energy gap), the temperature dependence of the magnetic penetration depth is well described by the equation

$$\lambda(T) = \lambda(T=0) \left[1 - \left(\frac{T}{T_c} \right)^4 \right]^{-1/2} . \qquad (2)$$

The solid line shown in Fig. 1(a) is derived from the substitution of Eq. (2) into Eq. (1), with $\lambda(T=0) = 1400$ Å. Except for small fluctuations at low temperatures ($T < 40$ K), the agreement between the standard theory and our experiment is excellent, which implies that the pairing in $Ba_2YCu_3O_{9-\delta}$ is of the conventional s-wave variety (i.e., there are no nodal points or lines in the energy gap function), contrary to various theoretical proposals,[9-11] which suggest magnetic fluctuations as the pairing mechanism, but in accord with exciton[12]—and phonon—mediated pairing. The phonon mechanism, however, seems to be ruled out by other experimental results.[13] The agreement with Eq. (2) is more readily seen in Fig. 2 where the relative incremental magnetic-field penetration depth $[\lambda(T) - \lambda(T=0)]/\lambda(T=0)$ is plotted as a function of $(T/T_c)^2$, where T_c is taken to be 80 K. The dashed line indicates the standard BCS behavior described by Eq. (2). We note that in the pure heavy-electron superconductor UBe_{13}, the experimental[14] $\lambda(T)/\lambda(T=0)$ deviates sub-

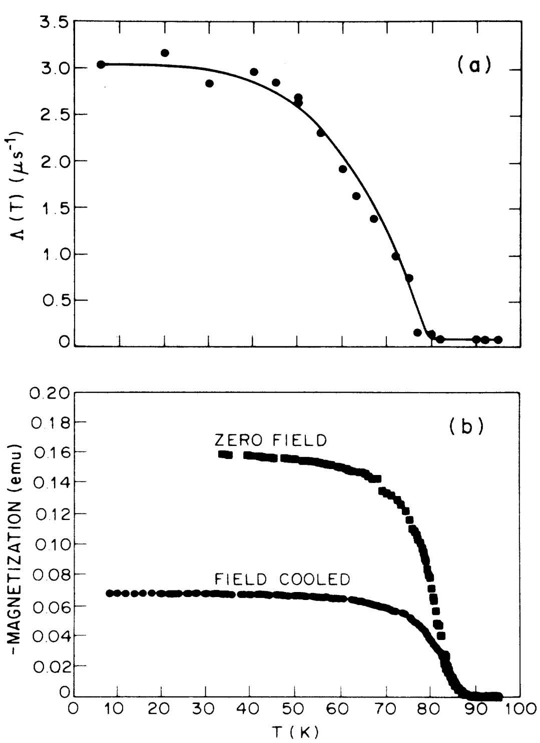

FIG. 1. Temperature dependence of (a) the Gaussian relaxation rate Λ obtained for a transverse field $H_{\text{ext}}=3.4$ kG (cooling in applied field), and (b) the magnetization ($H_{\text{ext}}=100$ Oe) measured in a field-cooled sample (circles) and a sample cooled in zero field (squares).

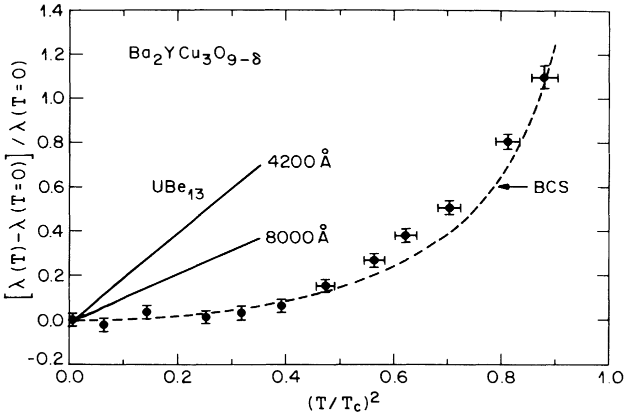

FIG. 2. The relative incremental magnetic-field penetration depth $[\lambda(T)-\lambda(T=0)]/\lambda(T=0)$ plotted against $(T/T_c)^2$ (circles). The dashed line represents the expected BCS behavior for ordinary superconductors as described by Eq. (2), while the solid lines represent the UBe_{13} data, assuming $\lambda(T=0)$ equal to 4200 and 8000 Å (as in Ref. 14).

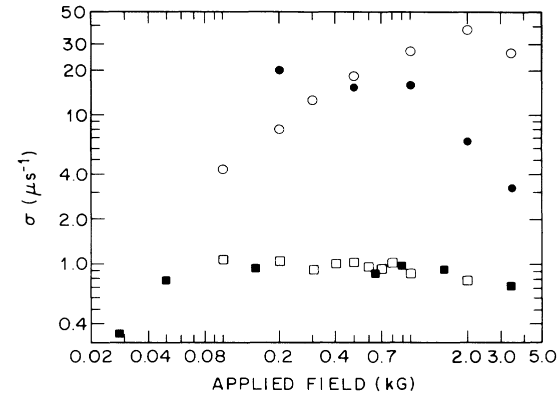

FIG. 3. Field dependence of σ (Gaussian linewidth) at 6 and 72 K for various sample histories. The open symbols correspond to data taken in increasing steps from 100 G, after zero-field cooling to 6 (circles) and 72 K (squares), and the filled symbols represent data taken in decreasing steps after field cooling in a field of 3.4 kG, to 6 (circles) and 72 K (squares).

stantially from the form of Eq. (2). The low-temperature data for UBe_{13} (Ref. 14) are plotted (solid lines) for comparison in Fig. 2, assuming $\lambda(T=0)$ equal to 4200 and 8000 Å. It is also interesting that Eq. (2) does not describe $\lambda(T)$ of $La_{1.85}Sr_{0.15}CuO_4$ very well, a result which may be understood in terms of the greater disorder in this highly doped compound as opposed to the nearly stoichiometric $Ba_2YCu_3O_{9-\delta}$ compound. As well, there is evidence that these materials deteriorate with age, particularly if exposed to high humidity.

The field dependence of σ (Gaussian linewidth) at 6 and at 72 K is shown in Fig. 3. The open circles represent data taken while increasing H_{ext} from 100 G after zero-field cooling to 6 K. As can be seen, $\sigma(H_{ext})$ increases monotonically until about 2 kG, where it reaches a maximum, and then begins to decrease again. The filled circles correspond to data taken on decreasing H_{ext} from 3.4 kG, after field cooling (to 6 K) at that field. Note that $\sigma(H_{ext})$ increases monotonically with decreasing field to about 500 G where it then levels off. The large history dependence observed is also clear evidence for flux pinning at 6 K. Other measurements,[2] made on the same sample, yield a value of 500 Oe for H_{c1}. At 72 K, there is little or no hysteresis observed, indicating an absence of flux pinning.

To summarize, the magnetic penetration depth (λ) has been measured in the high-T_c superconductor $Ba_2YCu_3O_{9-\delta}$. The value at 6 K, $\lambda \approx 1400$ Å, together with thermodynamic measurements,[2] indicates a charge-carrier density of $n=1.0\times10^{22}$ cm^{-3}. Also, by considering the extreme anisotropic limit, λ ($T=6$ K) was found to reduce to ≈ 1065 Å. The temperature dependence of λ was also found to be consistent (except for small fluctuations at low temperatures) with the standard form for ordinary superconductors, unlike the previous result[3] obtained with $La_{1.85}Sr_{0.15}CuO_4$. Thus, the pairing in $Ba_2YCu_3O_{9-\delta}$ appears to be of the conventional s-wave variety. Recent band-structure calculations[15] also indicate an anisotropy in the electronic structure of $Ba_2YCu_3O_{9-\delta}$ which might lead to an anisotropic penetration depth. Experiments are presently underway to investigate this possibility and to better determine the low-temperature behavior.

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