New Muon-Spin-Rotation Measurement of the Temperature Dependence of the Magnetic Penetration Depth in $YBa_2Cu_3O_{6.95}$

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(Received 28 October 1993)

We report muon-spin-rotation (μSR) measurements of the *a-b* magnetic penetration depth (λ_{ab}) in the vortex state of high quality single crystals of $YBa_2Cu_3O_{6.95}$. Contrary to earlier μSR studies on powders and crystal mosaics, $1/\lambda_{ab}^2$ shows a strong linear temperature dependence below 50 K which weakens with increasing magnetic field. These results support recent microwave cavity measurements in zero field and provide further evidence for unconventional pairing of carriers.

PACS numbers: 74.25.Bt, 74.25.Ha, 76.75.+i

Considerable debate has arisen over the nature of the electronic ground state in high-T_c superconductors such as $YBa_2Cu_3O_{7-\delta}$. Although pairing of charge carriers is almost certainly involved, the underlying symmetry of the pairing state (*s* wave, *d* wave, or other) has been the subject of a long and continuing controversy. Measurements of the temperature dependence of the magnetic penetration depth (λ) are one way to probe the nature of the low energy excitations and the pairing state. In a simple London model,

$$\frac{1}{\lambda^2}=\frac{4\pi n_s e^2}{m^* c^2}, \tag{1}$$

where n_s is the superfluid density and m^* is the effective mass of the carriers. Early muon-spin-rotation (μSR) studies on sintered powders and lower quality crystals of $YBa_2Cu_3O_{7-\delta}$ have concluded that $1/\lambda^2$ has a weak temperature dependence for $T \ll T_c$, suggesting there is an energy gap in the spectrum of excitations [1], as expected for conventional *s*-wave pairing. However, other techniques such as NMR [2] and infrared reflectance [3] failed to provide clear evidence for such a gap. Many of these latter experiments can be explained if there are nodes in the superconducting energy gap function, $\Delta_{\mathbf{k}}$, as predicted by some theories in which short range repulsive interactions play a dominant role in the pairing mechanism [4]. Recent microwave cavity perturbation measurements on high quality $YBa_2Cu_3O_{6.95}$ crystals have found a linear temperature dependence in λ below 30 K [5], consistent with line nodes in $\Delta_{\mathbf{k}}$ expected from singlet $d_{x^2-y^2}$-wave pairing [6]. Similar studies of thin films of $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_8$ have shown a quadratic increase in $\lambda(T)$ [7]. It has been proposed that the differences are due to impurity scattering, which result in a crossover from linear to quadratic behavior in a *d*-wave superconductor [8].

Although the microwave method has high precision, it is not sensitive to the absolute value of $\lambda_{ab}(0)$, only to *changes* in λ_{ab} as a function of temperature, and this only within the microwave skin depth of the surface. Consequently, such measurements leave some ambiguity as to the behavior of $1/\lambda^2$ and thus n_s. Muon spin rotation, on the other hand, gives a direct measure of the magnetic field distribution and λ_{ab} (the penetration depth in the *a*-*b* plane) in the bulk of the sample. In this Letter we present μSR measurements of $1/\lambda_{ab}^2$ in high quality single crystals of $YBa_2Cu_3O_{6.95}$ similar to those used in the microwave cavity perturbation studies [5]. Although $\lambda_{ab}(T=0)$ is close to that determined from earlier μSR studies on sintered powders and crystal mosaics, the temperature dependence is dramatically different. In particular, we observe a linear term in $\lambda_{ab}(T)$ below 30 K which is similar in magnitude to that reported in Ref. [5].

The present μSR study was carried out on a mosaic of three twinned crystals of $YBa_2Cu_3O_{6.95}$ which are of the highest quality currently available, as evidenced by low field magnetization, *a-b* plane resistivity, microwave surface resistance, and heat capacity measurements [9]. For example, the superconducting transition, determined by magnetization, occurred at 93.2 K with a transition width of less than 0.25 K. To ensure that each crystal had the identical oxygen concentration corresponding to the maximum T_c, all three crystals were carefully annealed prior to the experiment. For 3 d, the crystals were held in 1 atm of O_2 at 860 °C, followed by 14 d at 450 °C before rapid cooling to room temperature. The three crystals, which have a total mass of 53 mg, were assembled to provide a total area of 36 mm^2 perpendicular to the *c* axis and to the muon beam.

The measurements were performed on the M15 beam line at TRIUMF which produces a beam of spin polarized positive muons of mean momentum 28 MeV/*c*. After passing through a 1 cm collimator and a thin muon defining counter, a small fraction of the incoming beam came to rest in the crystals (30000 $\mu^+ s^{-1}$ stops out of 200000 $\mu^+ s^{-1}$ incoming). A novel experimental setup [10] was used to eliminate most of the background signal from the muons which missed the sample. This allowed us to obtain much higher quality data than was previously possible for such small crystalline samples. Trans-

0031-9007/94/72(5)/744(4)$06.00

verse-field- (TF-) μSR spectra with approximately 2×10^7 muon decay events were taken under conditions of field cooling in magnetic fields of 0.5 and 1.5 T applied along the c axis. For hard type II superconductors in the field region $H_{c_1} \leq H \ll H_{c_2}$, the magnetic field distribution arising from the vortex lattice is determined primarily by the London penetration depth λ, the length scale over which magnetic flux leaks into the superconducting region around the vortex cores.

Since the muons stop randomly on the length scale of the flux lattice the muon spin precession signal provides a random sampling of the internal field distribution in the vortex state. Figure 1(a) shows a typical muon spin precession signal displayed for convenience in a reference frame rotating at about 4 MHz below the Larmor precession frequency of a free muon. Figure 1(b) shows the real amplitude of the Fourier transform, which is a good approximation to the internal field distribution. The sharp peak at 67.3 MHz in Fig. 1(b), which accounts for approximately 13% of the total signal amplitude, is attributed to the residual background signal from muons which miss the sample. Figure 1(c) shows the frequency spectrum after field cooling in 0.5 T and then lowering the applied field by 11.3 mT. Note that the background signal shifts down by 1.5 MHz in response to the change in the applied field, whereas the signal from muons in the sample remains unchanged to within experimental error. This demonstrates the strong pinning of the vortex lattice at low temperatures. Also apparent is the absence of any background peak in the unshifted signal, which implies that the sample is free of appreciable nonsuperconducting inclusions. The asymmetric frequency distribution shown in Figs. 1(b) and 1(c) has the basic features expected for a triangular vortex lattice. The sharp cutoff at low frequencies is due to the minimum in the field profile occurring at the midpoint of three adjacent vortices. The peak arises from the saddle point midway between two adjacent vortices, whereas the long tail at high frequencies is due to the region around the vortex core.

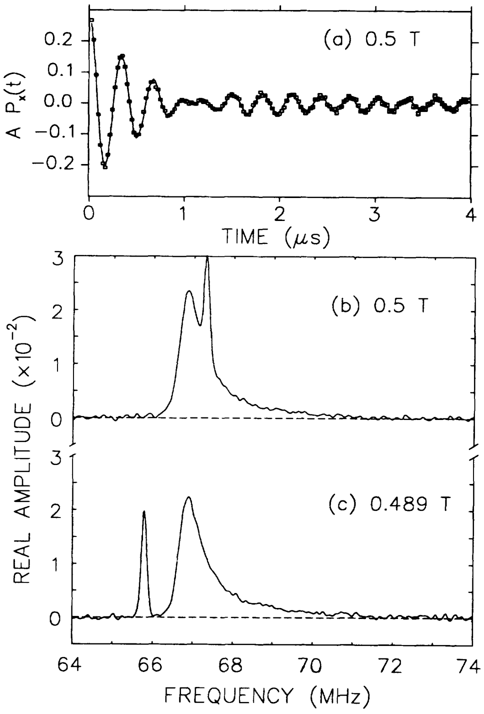

FIG. 1. (a) The muon spin precession signal in $YBa_2Cu_3O_{6.95}$ after field cooling to 5.4 K in a magnetic field $H=0.5$ T applied parallel to the c axis. (b) The Fourier transformation of (a) using a Gaussian apodization with a 3 μs time constant. (c) Same as in (b) except that the field was lowered by 11.3 mT after field cooling to 6 K.

The curve in Fig. 1(a) is an example of a fit by a theoretical polarization function generated under the following assumptions.

(1) A perfect flux lattice gives rise to an internal field distribution $n(B)$ obtained from the field profile $B(\mathbf{r})$ given by a modified London model [11]:

$$B(\mathbf{r}) = B_0 \sum_{\mathbf{K}} \frac{e^{-i\mathbf{K}\cdot\mathbf{r}} e^{-\xi^2 K^2/2(1-b)}}{1+K^2\lambda_{ab}^2/(1-b)}, \qquad (2)$$

where $\mathbf{K}$ is a reciprocal vortex lattice vector, ξ is the coherence length, λ_{ab} is the magnetic penetration depth in the a-b plane, B_0 is the average internal magnetic field, and $b=B_0/B_{c_2}$, which is negligible for the magnetic fields being considered here. The second exponential introduces an upper cutoff, yielding a finite value at the vortex core. In Eq. (2) we are implicitly assuming that anisotropy has a negligible effect, which is valid for H applied along the c axis and in the absence of any significant a-b anisotropy.

(2) The Ginzburg-Landau parameter $\kappa=\lambda_{ab}/\xi$ is independent of temperature. Although this is strictly valid only for weak coupling s-wave superconductors, the line shapes in the low field region being considered here are not very sensitive to κ. The best overall fit was obtained with $\kappa=68$, which is close to the value of 69(1.4) determined from recent line-shape measurements on similar crystals in higher magnetic fields [12]. Increasing κ to 73 changes $\lambda_{ab}(0)$ by less than 0.3 nm.

(3) The field distribution in the sample is a convolution of $n(B)$ and a Gaussian distribution which takes into account other line broadening effects [12]. This leads to a complex muon polarization,

$$P_x(t)+iP_y(t) = e^{-(\sigma_d^2+\sigma_f^2)t^2/2}\int n(B)e^{i\gamma_\mu B t}\,dB, \qquad (3)$$

where $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ define the plane of precession and γ_μ is the gyromagnetic ratio of the muon. The small and constant nuclear dipolar contribution $\sigma_d < 0.13\ \mu s^{-1}$ was determined from a run just above T_c. The parameter σ_f allows for further broadening of the field distribution [11]. A linear correlation was observed between σ_f and $1/\lambda_{ab}^2$ so that in the final analysis σ_f was assumed to be proportional to $1/\lambda_{ab}^2$. From global fits to the data the proportionality constants at 0.5 and 1.5 T were determined to be

0.0293(10) and 0.0258(10) $\mu m^2 \mu s^{-1}$, respectively. The uncertainty in this constant leads to an additional systematic uncertainty in $\lambda_{ab}(0)$ of about 1.5 nm. The linear correlation and the magnitude of the broadening can be explained if the vortices are randomly displaced by about 5% relative to their positions for an ideal triangular lattice as a result of pinning forces [12].

The temperature dependence of λ_{ab} at 0.5 T (circles) and 1.5 T (crosses) is shown in Fig. 2. Both sets of data exhibit a clear linear term below 30 K. The solid curve represents microwave measurements of the change in penetration depth taken in zero static magnetic field [5], where for the purpose of comparison $\lambda_{ab}(0)$ is chosen to be 0.1490 μm. Surprisingly, $\lambda_{ab}(T)$ from the microwave data appears to agree slightly better with the μSR data at the higher magnetic field of 1.5 T. However, the overall agreement is remarkable considering the very different nature of the measurements. For example, in the microwave studies the shielding currents circulate around the perimeter of the sample within a penetration depth of the surface, whereas in the present study they circulate around the vortex cores in the *a-b* plane throughout the volume of sample.

Figures 3(a) and 3(b) show the temperature dependence of $1/\lambda_{ab}^2$, which is directly proportional to the superfluid density [see Eq. (1)]. Note that at 0.5 T [see Fig. 3(a)] the linear dependence of $1/\lambda_{ab}^2$ vs T extends out to 50 K. The solid line is a fit by $\lambda_{ab}^{-2}(T)=\lambda_{ab}^{-2}(0)\times[1-\alpha T-\beta T^2]$ with $\lambda_{ab}(0)=0.1451(3)$ μm, $\alpha=7.2(1)\times10^{-3}$ K^{-1}, and β set to zero, where the quoted errors are purely statistical. In Fig. 3(b) the solid curve is a fit to the data at 1.5 T with fitted parameters $\lambda_{ab}(0)=0.1496(3)$ μm, $\alpha=3.4(5)\times10^{-3}$ K^{-1}, and $\beta=4.5(8)\times10^{-5}$ K^{-2}. The weakening of the linear term at the higher magnetic field is clear. It has been predicted that impurity scattering in a *d*-wave superconductor can give rise to an increase in λ_{ab} at low temperatures, thereby weakening the linear term [8]. It is possible that a static magnetic field may have a similar effect, possibly due to quasiparticle scattering off the vortex cores. The unusual gap function $\Delta_{\mathbf{k}}$ in a *d*-wave superconductor may also result in field dependence of the magnetic properties [13]. Although these have not been fully elucidated for the vortex state, one might expect from Ref. [13] the effective magnetic penetration depth in the vortex state to vary with the average current density. Using Eq. (2) one finds that the volume average of $\mathbf{J}=\nabla\times\mathbf{B}/\mu_0$ increases in magnitude from about 2.0×10^7 A cm^{-2} at 0.5 T to about 3.0×10^7 A cm^{-2} at 1.5 T.

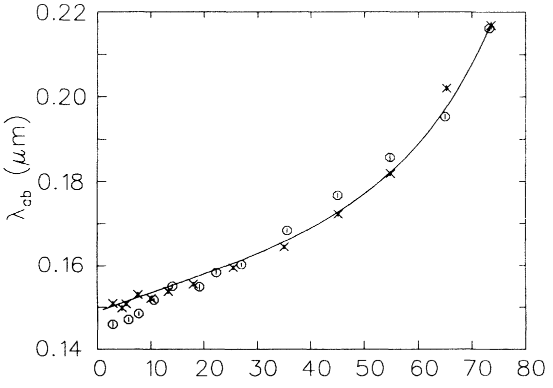

FIG. 2. The temperature dependence of λ_{ab} at 0.5 T (circles) and 1.5 T (crosses). The solid line shows the microwave measurements of $\Delta\lambda_{ab}(T)$ in zero field from Ref. [5] assuming $\lambda_{ab}(0)=0.1490$ μm.

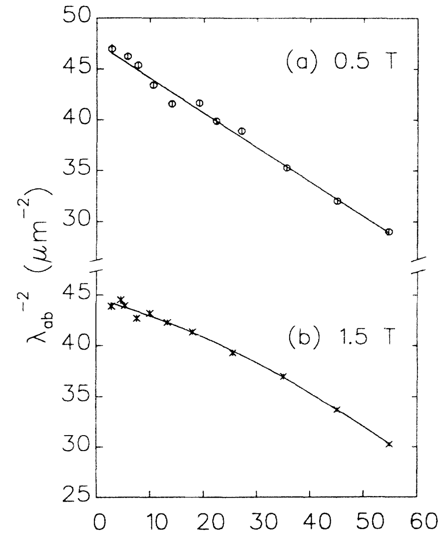

FIG. 3. The temperature dependence of $1/\lambda_{ab}^2$ in a magnetic field of (a) 0.5 T and (b) 1.5 T. The parameters for the fitted solid straight line in (a) and quadratic curve in (b) are given in the text.

The present results are difficult to reconcile with many earlier μSR works on sintered powders and single crystals [1]. In particular, there are no previous reports of such a prominent linear temperature dependence in $1/\lambda_{ab}^2$. This disagreement cannot be attributed to the improper fitting functions used in many previous works; for example, the main features in Figs. 2 and 3 are still present if one crudely estimates the second moment of the field distribution ($\propto 1/\lambda_{ab}^2$) by fitting by a Gaussian distribution of internal fields—the analysis procedure used in most of the previous work. With the exception of Ref. [12], all previous μSR studies were made on material with transition temperatures below that of the crystals in the present study and often below 90 K. If this reduction in T_c were due to impurities or other crystalline imperfections, one might expect a T^2 dependence in those samples [8], which is difficult to distinguish from BCS behavior without precise low temperature data. This, along with the fact that statements about the pairing mechanism were made on the basis of the overall behavior of λ_{ab} rather than that from the critical low temperature region, may have led to misinterpretation in some cases.

In conclusion, we have observed a linear temperature variation of $1/\lambda_{ab}^2$ in the vortex state of high quality crystals of $YBa_2Cu_3O_{6.95}$. These results differ qualitatively from earlier reports on μSR studies of sintered powders and crystal mosaics, but they support recent microwave cavity measurements on similar crystals. In addition, we find evidence that $\lambda_{ab}(T)$ depends on the magnetic field. Both results are further evidence of unconventional pairing of carriers in copper oxide superconductors.

We would like to thank Keith Hoyle and Curtis Ballard for technical assistance. This work is supported by the Natural Sciences and Engineering Research Council of Canada.

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