Transparency of the *ab* Planes of $Bi_2Sr_2CaCu_2O_{8+\delta}$ to Magnetic Fields

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A sample composed of many $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals was cooled to 2 K in a magnetic field of 100 G at 45° from the **c** axis. Muon-spin-rotation measurements were made for which the polarization was initially approximately in the **ab** plane. The time dependent polarization components along this initial direction and along the **c** axis were obtained. Cosine transforms of these and subsequent measurements were made. Upon removing the applied field, still at 2 K, only the **c** axis component of the field remained in the sample, thus providing microscopic evidence for extreme 2D behavior for the vortices even at this temperature. [S0031-9007(97)05026-6]

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Many superconductors are for the most part isotropic in the sense that the penetration depth λ is nearly the same in all directions and the supercurrents are not dependent upon their direction of flow. For isotropic superconductors the magnetic fields may be found by minimizing the free energy [1]:

$$\mathcal{F} = \frac{1}{8\pi}\int_V (b^2 + \lambda^2|\nabla \times \vec{b}|^2)\,dV\,. \quad (1)$$

The currents form vortices as illustrated in the top portion of Fig. 1, which shows that the vortices do not depend on their orientation with respect to the crystalline axes.

In contrast the cuprates are quite anisotropic. For $YBa_2Cu_3O_7$ (YBCO), it has been found sufficient to introduce an effective mass tensor to represent this anisotropy. Thus one finds the fields from the minimization of [2–4]:

$$\mathcal{F} = \frac{1}{8\pi}\int_V [b^2 + \lambda^2 m_{ij}(\nabla \times \vec{b})_i(\nabla \times \vec{b})_j]\,dV\,. \quad (2)$$

The effective reduced mass tensor m_{ij} expresses the anisotropy and m_c/m_{ab}, the ratio of the mass along **c** to mass along the **a** or **b** is a measure of this anisotropy. For YBCO this ratio is about 25 [5]. The vortices that then form have currents which are not everywhere perpendicular to their axes. This is shown in the lower left portion of Fig. 1. This model produces vortices of a 3D tilted nature and has average fields parallel to the axis of this tilted vortex even for arbitrarily large masses along the **c** axis.

For $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (BSCCO) the anisotropy is of the order of 3000 [6]. Such extreme anisotropy had previously led Lawrence and Doniach [7] to introduce a model in which the weak coupling along the **c** axis is via Josephson tunneling. Clem [8] has introduced the notion of "pancake" vortices which are confined to the CuO planes for these extreme anisotropic systems. The general picture is shown schematically in the bottom center of Fig. 1. Clem [8] and Artemenko and Kruglov [9] have shown how one may calculate the magnetic fields inside the sample in this situation. Clem [10] has further shown

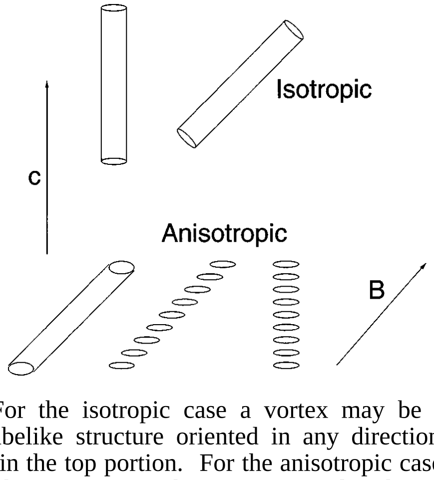

FIG. 1. For the isotropic case a vortex may be considered to be a tubelike structure oriented in any direction. This is illustrated in the top portion. For the anisotropic case, one may have tubelike structures with currents tipped with respect to the axis or separated pancakes of current; see the text.

that the equilibrium arrangement in the limit of very weak coupling is like that shown in the right lower portion of that figure, i.e., the pancakes of current line up on top of each other along the **c** axis while the field in the **ab** planes penetrates freely and unshielded.

Yamaguchi *et al.* [11] have investigated the dimensionality of the vortex magnetization state as a function of magnetic field tilt angle and temperature for BSCCO by dc magnetization measurements. They found that at low temperature, below 30 K, there seemed to be three dimensional coupling of the vortices into tubes, whereas at higher temperature they concluded that the two dimensional coupling was appropriate. This is in contrast to what one might expect based on the temperature dependence of the coherence length along the **c** axis. At low temperatures, ξ_c in BSCCO becomes less than the spacing between CuO_2 planes, which might suggest a more 2D character of the vortices at low temperature.

This study is an investigation of the vortex fields at 2 K using an extension of the usual muon-spin-rotation (μSR) techniques. For a general background on the μSR technique, see the reviews by Schenck [12], Brewer and Crowe [13], or by Chappert [14]. For the general aspects of our extension to the technique, see the monograph by Greer and Kossler [15].

We used the M20 beam line at TRIUMF. This beam line allows one to rotate the muon's polarization from roughly along the beam to approximately vertical. We denote the upstream beam axis **z**, the vertical by **y**, and use $\mathbf{x} = \mathbf{y} \times \mathbf{z}$.

Three pairs of coils were available. A large Helmholtz pair aligned along the beam axis could produce 5 kG. A vertical pair could produce about 100 G as could a pair aligned along the **x** axis. Thus, fields at the 100 G level could be produced in arbitrary directions.

The sample was placed in a transversely oriented flow cryostat equipped with calibrated temperature sensors. A thin scintillator was placed just upstream of the cryostat entrance window (about 0.025 mm thick).

The sample was made from multiple high purity single crystals which were similar to those used for a previous study [16] with the exception that the present crystals have been annealed in an oxygen atmosphere at 560 °C for about 18 h and quenched, resulting in a $T_c = 85(1)$ K. The transition width is about 1° as determined from magnetometry. The 2212 materials are known to be nonstoichiometric. The stoichiometry here is expected to be similar to the BSCCO annealed samples described by Mitzi *et al.* [17]. All were arranged so that their **c** axes were parallel to the beam axis. The sample had a total mass of 0.6 g and an overall diameter of 20 mm. The individual crystals were of various sizes and shapes and were typically about 2×2 mm across and less than 0.1 mm thick along the **c** direction. The sample was held between very thin x-ray Mylar and was mounted on high purity silver in which muons do not depolarize.

The detector placement is shown in Fig. 2. The data were collected in the (U-D) and (F-B) detector pairs.

The detection rate in a detector of direction $\vec{d}$ is equal to

$$D(t) = N(t)a[1 + \epsilon\vec{P}(t) \cdot \vec{d}], \tag{3}$$

where $N(t)$ is the muon decay rate in the sample and a and ϵ account for the detector efficiency and sensitivity to the muon polarization $\vec{P}(t)$. We applied a field in the **x** direction to obtain the parameters a and ϵ and from them $\vec{P}(t) \cdot \vec{d}$ and $\vec{P}(0)$. In the presence of a unique magnetic field $\vec{b}$ the polarization $\vec{P}$ precesses around $\vec{b}$ and thus

$$\begin{aligned}\vec{P}(t) = {} & \left(\frac{\vec{P}(0) \cdot \vec{b}}{b}\right)\frac{\vec{b}}{b} \\ & + \left[\vec{P}(0) - \left(\frac{\vec{P}(0) \cdot \vec{b}}{b}\right)\frac{\vec{b}}{b}\right]\cos\omega t \\ & + \left(\frac{\vec{P}(0) \times \vec{b}}{b}\right)\sin\omega t\,,\end{aligned} \tag{4}$$

where $\omega = \gamma_\mu b$. If the field is no longer unique, but has a distribution of values, as is the case for type II superconductors with vortices penetrating the sample, then one averages over the $\vec{P}(t)$ with appropriate weights for the field $\vec{b}$.

The spin-rotated mode on M20 has $\vec{P}(0)$ approximately in the **y**, U-D direction. Assuming $\vec{P}(0)$ is parallel to **y**,

$$P_z(t) = \frac{b_z b_y}{b^2}(1 - \cos\omega t) - \frac{b_x}{b}\sin\omega t \tag{5}$$

and

$$P_y(t) = \frac{b_y^2}{b^2} + \frac{b_z^2 + b_x^2}{b^2}\cos\omega t\,. \tag{6}$$

When cosine transforms are performed on $P_z(t)$ and $P_y(t)$ only those components with $b = \omega/\gamma_\mu$ will be selected from the distribution of fields. We thus obtain

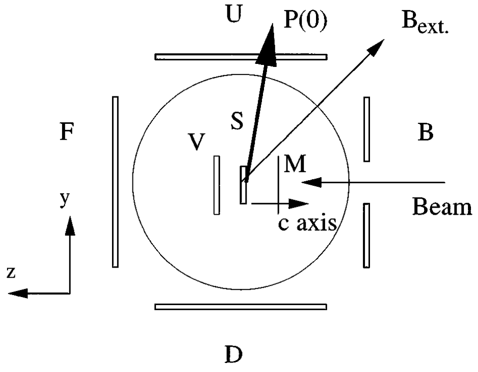

FIG. 2. A schematic view of the experimental arrangement. The positron detectors are labeled U, D, F, and B for up, down, forward, and backward, respectively. The initial muon polarization $P(0)$ is approximately vertical. The applied magnetic field direction, when it was on, was at approximately 45° from the beam axis toward vertical.

[15] the Fourier amplitudes:

$$\tilde{P}_z(\omega) = \frac{dn(b)}{db} \frac{\langle b_z b_y(\omega) \rangle}{b^2} \tag{7}$$

and

$$\tilde{P}_y(\omega) = \frac{dn(b)}{db} \frac{\langle b_z^2(\omega) + b_x^2(\omega) \rangle}{b^2} \,. \tag{8}$$

Here dn/db is the relative probability of the field b and the terms enclosed within $\langle \ldots \rangle$ refer to the average value of the expression at the given ω. Note that if fields everywhere pointed in the same direction, as in isotropic superconductors, the ratio of fields factors in these cosine transforms would be dependent on the direction, but not the magnitude of the field. Then $\tilde{P}_z(\omega) \propto \tilde{P}_y(\omega)$ and the cosine transforms have exactly the same shape.

After detector calibration with the sample above T_c, a field of approximately 100 G was applied 45° from the beam axis in the **xy** plane and the temperature was then slowly lowered to 2 K.

The cosine transforms of data taken in this configuration are shown as solid curves in the top portion of Fig. 3. For both detector pairs one sees a strong peak centered near 8.5 Mrads^{-1} expected for a 100 G external field.

Immediately after taking this data the external field was turned off while maintaining the temperature at 2 K. The cosine transforms for this zero field arrangement are shown in the bottom portion of Fig. 3. There are two striking features to observe. First, the peak from the F-B data is now completely *missing*. The disappearance of this peak may be simply understood in that the muons are precessing around a field completely aligned along the **c** axis so that the angle the spin makes with respect to this direction is constant. Second, the peak in the U-D data has *shifted* to about 70 G, as would be expected for precession about only the field component along the **z** direction, i.e., $\langle b_z \rangle \approx 70$ G and $b_y = 0$.

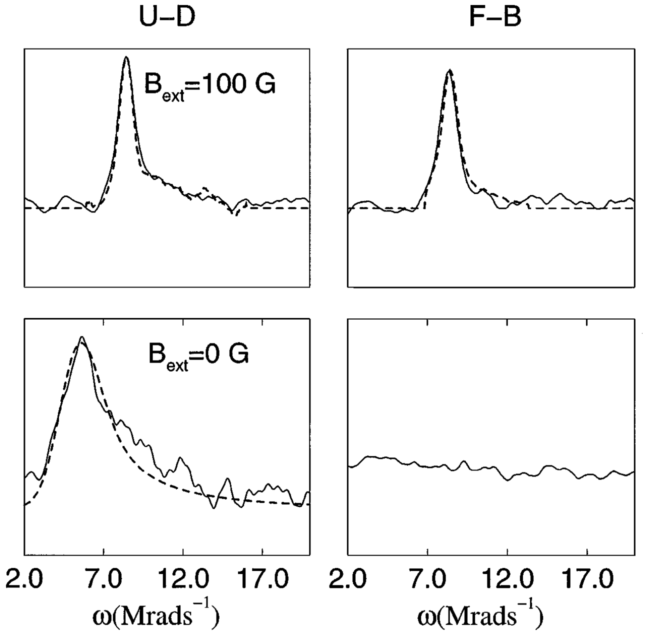

FIG. 3. Solid curves are Fourier transforms for the data from the U-D and F-B detector arrays for BSCCO single crystals. The top set was for field cooled and the field still applied. The bottom pair were taken immediately after Bext was set to 0. All data were at 2 K. The dashed line in the upper left (upper right) is our prediction from the data of the lower left (upper left); see text. The dashed line of the lower left is derived from a vortex lattice model with $\lambda_{ab} = 2000$ Å and a local field variation of 13 G.

With the external field off, the U-D cosine transform for the BSCCO remained invariant at 2 and 10 K for time periods of at least an hour. This implies that the field along **c** axis was pinned at these temperatures. If the vortices were truly three dimensional, as in the tilted stack structure in the lower middle of Fig. 1, and if they maintained a 3D integrity through the sample as the field was turned off, vortices at their ends would have to move a distance ≈0.05 mm, half the crystal thickness, in order to form their final vertical stacks. We believe such motion to be inconsistent with the observed pinning. Further, to maintain a constant magnetic flux through the sample, pancake vortices would have had to enter and leave through the sample sides as the field was reduced to zero. This too is inconsistent with the observed pinning. We conclude that, even with the field on, the pancake vortices must not be arranged with tilted correlations which would lead to a trapped tilted average field, but must have **c** axis aligned correlations. With only pinned **c** axis correlations, the magnetic field in the **ab** planes is just the applied field component, i.e., even at 2 K the **ab** planes are *transparent* to magnetic fields. This should be compared with the suggestion of Clem [10], illustrated at the lower right of Fig. 1, that for sufficiently weak interplanar coupling, the vortices would form stacks along the **c** axis.

To test this transparency notion we predict the Fourier transform of the top left of Fig. 3 from the data of the lower left of Fig. 3 as follows: When an applied field is present, the local magnetic field would arise from a **z** distribution dn/db_z, as determined from the data of the lower left of Fig. 3 plus a fixed component b_y in the **y** direction. We assume that the **x** component of **b** is small which is at least plausible since the applied field is in the **yz** plane. The probability of b is then

$$\frac{dn}{db} = \frac{dn}{db_z} \frac{db_z}{db}; \qquad b^2 = b_y^2 + b_z^2 \,. \tag{9}$$

Thus from Eq. (8) we expect

$$\tilde{P}_y(\omega) \propto \frac{dn}{db_z} \frac{b_z}{b} \,. \tag{10}$$

The dashed curve in the top left Fig. 3 is the result of this transformation of the data of the bottom left of that figure plus a small residual background component. Further, we can predict from Eqs. (7) and (8) that

$$\tilde{P}_z(\omega) = \frac{b_y}{b_z} \tilde{P}_y(\omega) \,. \tag{11}$$

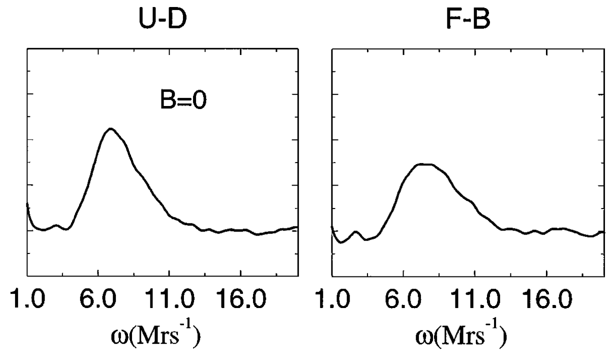

FIG. 4. Solid curves are Fourier transforms for the data from the U-D and F-B detector arrays for the case of a large YBCO single crystal with inclusions. The sample was field cooled to 2 K and then the field was turned off. The data were taken at 10 K.

The dashed curve in the upper right of Fig. 3 is this prediction. The less pronounced high frequency tail seen in these F-B data as compared to the U-D data agrees with the prediction from Eq. (7), and may be seen as a consequence of the large b components being associated with large b_z components. Thus, we see that the notion of transparency also leads to predictions for the applied field cases in excellent agreement with experiment.

For comparison, we performed a similar experiment using a large single crystal of YBCO with pinning inclusions. As for BSCCO, the YBCO sample was first field cooled to 2 K in an applied field of about 100 G, 45° from the **c** axis, and at 2 K the applied field was then turned off. The cosine transforms for our data at 10 K and applied field off are shown in Fig. 4. One sees that for this case there are indeed peaks in both the U-D and F-B detectors and the average precession frequency corresponds to a mean field of 100 G. This is what would be expected for the case of 3D vortices completely pinned approximately [18] along the direction of the external field during field cooling.

In summary: We found that even at 2 K, a 100 G applied field 45° from the **c** axis seems to penetrate in the form of vortices with correlations only along the **c** direction, while the superconductor appears transparent to field components in the **ab** plane.

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