Evidence for Flux-Lattice Melting and a Dimensional Crossover in Single-Crystal $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ from Muon Spin Rotation Studies

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The *microscopic* magnetic field distribution in the mixed state of single-crystal $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ has been measured using the muon spin rotation technique. A study of the line shapes as a function of temperature and magnetic field gives evidence for an abrupt change of flux-lattice structure which is attributed to the presence of a flux-lattice melting line in the B-T phase diagram. In addition, the data suggest the existence of a crossover field above which the flux structure is more 2D in nature.

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The field-temperature (B-T) phase diagram for the high-temperature superconductors has been the subject of much experimental [1–5] and theoretical [6–11] investigation. Of particular interest is the case of the Bi-based compounds, where a strong anisotropy may lead to a variety of flux-vortex structures (see, e.g., [12]). Many techniques which measure the bulk properties of single crystals show the presence of an irreversibility line in the B-T plane, below which hysteretic behavior is observable (see, e.g., [3,5]), but the nature of the associated microscopic processes is as yet far from clear. The muon spin rotation technique (μ^+SR) provides a measure of the microscopic field distribution inside the bulk of a type-II superconductor, and in addition may yield information on the dynamics of the vortex state. Here we present results of a μ^+SR investigation of the low-field region of the B-T plane of the high-T_c material $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ (BSCCO), which demonstrates the existence of a sharp transition associated with the flux structure. This transition is found to occur close to the irreversibility line, and may be associated with the transition from a vortex solid to a vortex liquid. A further transition has also been observed as a function of field, which shows characteristic changes of the μ^+SR line shape expected from a dimensional crossover of the vortex structure. To our knowledge these are the first such observations using a *microscopic* probe of the vortex structure.

The μ^+SR measurements were performed at the Paul Scherrer Institute, Switzerland, on high quality single crystals of BSCCO. The crystals were grown as described in Ref. [13], and have a $T_c \approx 84$ K as determined by magnetization measurements. The sample consisted of a mosaic of eight crystals, each typically 5 $mm^2 \times 0.5$ mm, with the crystallographic c direction parallel to the shortest dimension and mounted perpendicular to the surface of an Fe_2O_3 plate. A magnetic field was applied parallel to the c axes of the crystals, and positive muons were incident on the sample with their spin-polarization vector perpendicular to the applied field. Time-differential μ^+SR spectroscopy was employed (see, e.g., [4]) from which one can deduce the probability distribution of the local magnetic field of the vortex state by measuring the time evolution of the μ^+ spin polarization [14].

For a given flux structure one can calculate the expected probability distribution $p(B)$ of the internal field (see, e.g., [15]). The measurement of $p(B)$ via μ^+SR allows an investigation of the details of the flux structure, such as the effects of random pinning [15] and the dimensionality of the vortex structure [16]. Figure 1(a) shows the probability distribution of the local internal field $p(B)$ for the sample at a temperature of 5 K, after cooling in an applied field of 5.2 mT. This was obtained via a Fourier transform of the muon time spectrum using a maximum entropy technique, described elsewhere [17]. This line shape shows features which are clear indications of a 3D flux structure (see, e.g., [15]), notably the long "tail" at fields higher than the applied, which arises from regions close to the vortex cores. This is the first such clear observation of a 3D flux-lattice line shape in this material. Also included is a simulation using a 3D triangular flux lattice at the same applied field, which, as can be seen, is a reasonable representation of the data. The contribution to the spectrum from the muons not stopping in the sample was assessed using a zero-field cool technique (as described in Ref. [18]), and was found to be negligibly small. Figure 1(b) shows the distribution found for the sample at 54.0 K after cooling in an applied field of 45.4 mT, so that it lies in a region of the B-T plane below the irreversibility line, and a second line shape obtained after the sample had been warmed to a temperature of 63.8 K, above the irreversibility line but still well below T_c. The shape of the latter spectrum is clearly different, with a loss of the high-field tail, reflecting a marked change of vortex structure. In order to quantify such changes we define a ratio α, derived from the third and second moments of the line shape, as $\alpha = \langle(\Delta B)^3\rangle^{1/3}/\langle(\Delta B)^2\rangle^{1/2}$. This is a dimensionless measure of the asymmetry of the line shape, the variation of

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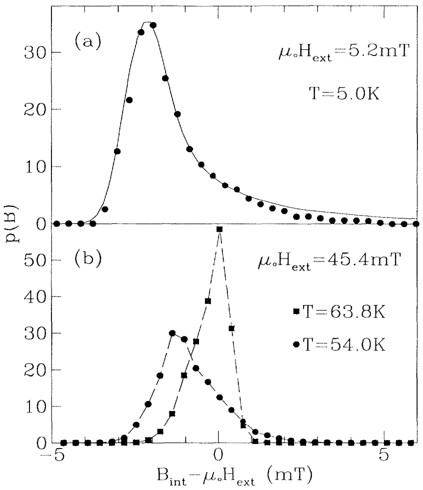

FIG. 1. The probability distribution of the internal magnetic fields in $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$. (a) At $\mu_0 H_{ext}=5.2$ mT and $T=5.0$ K, where the asymmetric line shape shows features characteristic of a vortex-line structure; the solid line is the result of a simulated ideal triangular lattice, using a penetration depth of $\lambda \approx 1800$ Å. The simulation has been convoluted with a Gaussian of width 2.4 G to simulate the effects of lattice imperfection and instrumental resolution; (b) at $\mu_0 H_{ext}=45.4$ mT, for (i) $T=54.0$ K (circles), just below the irreversibility line (see Fig. 3); (ii) at $T=63.8$ K (squares), just above the irreversibility line, showing a significantly different line shape. The dashed lines are guides to the eye.

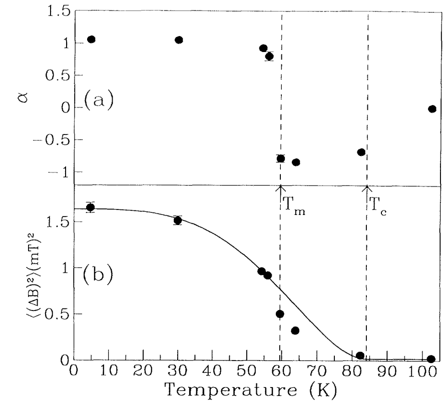

FIG. 2. The temperature dependence of (a) the line-shape asymmetry parameter $\alpha=\langle(\Delta B)^3\rangle^{1/3}/\langle(\Delta B)^2\rangle^{1/2}$ (see text) and (b) the second moment of the field distributions after field cooling at 45.4 mT. Note the sharp drop in the asymmetry of the line shape around $T_m=59.5$ K and the corresponding deviation of the second moment from the fit of the data by Eq. (1) over the temperature range $5 \leq T \leq 55$ K [solid line in (b), with $n=3.3$].

which reflects underlying changes in the vortex structure. In Fig. 2(a) α is plotted as a function of temperature, for an applied field of 45.4 mT. Here it can be seen that α changes *sign* abruptly within a temperature range of less than 2 K, indicating the existence of a phase transition in the vortex structure. Moreover, the negative value of α, obtained for the line shapes observed above the transition, reflects a substantial shift of probability away from the high-field tails; this is totally inconsistent with the existence of a triangular or square static 3D lattice. It is possible that the truncation of the high-field tail may reflect either a motion of the vortices [19] or a reduced dimensionality of the vortex structure [20], both of which could cause an effective smearing of the vortex cores. Plotted in Fig. 2(b) is the temperature dependence of the second moment $\langle(\Delta B)^2\rangle$ of the field distribution. For a static array of 3D flux lines the second moment is a measure of superconducting penetration depth λ of the material (see, e.g., [21]), which is generally expected to follow a temperature dependence of the form

$$\lambda(T)=\lambda(0)/(1-t^n)^{1/2}, \tag{1}$$

where $t=T/T_c$ is the reduced temperature and in particular $n=4$ for the two-fluid model. It can be seen from Fig. 2(b) that the onset of the change of line shape, as indicated by the sudden decrease of the line-shape asymmetry in Fig. 2(a), is accompanied by a drop in the value of the second moment $\langle(\Delta B)^2\rangle$ from that expected by extrapolation of the low-temperature data to T_c [the solid line is a fit of the low-temperature data $5 \leq T \leq 55$ K by Eq. (1), yielding $n=3.3$]. From the abruptness of the observed changes in the second moment and α it is clear that there is a sharp transition of the vortex structure, which we associate with flux-lattice melting. Furthermore, this phase transition has been observed at several fields from 5.2 to 401 mT, and its temperature T_m has been ascertained with varying degrees of precision. The results are given in Fig. 3. The transition line in the phase diagram which is formed by these points lies close to the irreversibility line for samples from the same source, as determined by ac-susceptibility measurements at a frequency of 87 Hz [3,22].

In highly anisotropic systems the flux structure may consist of 2D layers of "pancake" vortices (see, e.g., [12]), which at low fields may couple via Josephson and magnetic interactions to form 3D line vortices. It has been shown that disorder induced by random pinning in such a system, which reduces the correlations between the positions of vortex cores in adjacent layers, may truncate the high-field tail, reduce the second moment and the asymmetry of the line shape, and may also cause the peak field to move towards the applied field [16,19,20]. In Fig. 4 the low-temperature value of our line-shape asymmetry parameter α, obtained in each case after field cooling the sample, is plotted as a function of field. This indicates a change of vortex structure with increasing field, with a sharp drop in the magnitude of α beginning at $B \sim 50$ mT. An example of the more symmetric line shape found above this field-induced transition is shown in the inset of Fig. 4 (see also Ref. [18]), and appears to be centered at the applied field. While one also observes in this line

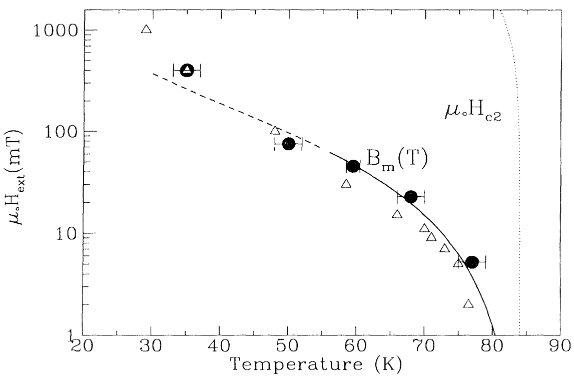

FIG. 3. The points in the B-T plane corresponding to the melting temperature as measured by the change in μ^+SR line shape (circles). The transition has been operationally defined as the onset of the change from a negative to a positive third moment of the field distribution, as indicated by the arrow of Fig. 2. The solid line is a fit of the three lowest field points to the 3D melting function Eq. (2) (see text), shown extended into the 2D region as a dashed line. Also shown is the irreversibility line as measured by ac susceptibility (triangles) taken from Ref. [3]. The H_{c2} line (dotted line) is the function $H_{c2}(0)(1-t)$, with $H_{c2}(0)=44$ T [6].

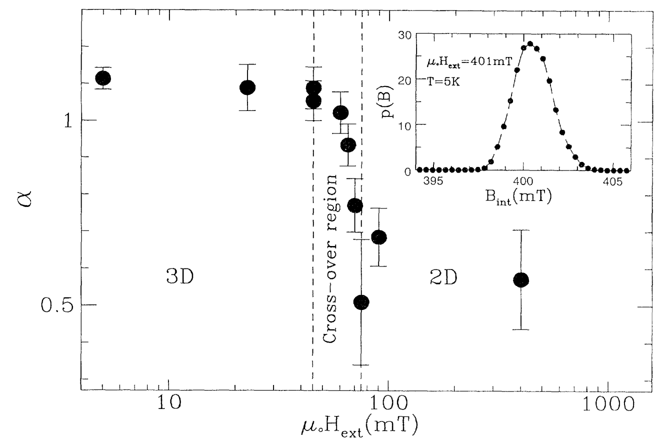

FIG. 4. The field dependence of the line-shape asymmetry parameter $\alpha = \langle(\Delta B)^3\rangle^{1/3}/\langle(\Delta B)^2\rangle^{1/2}$ at $T=5$ K, after field cooling at each field. The large drop in magnitude beginning at $B\sim50$ mT is believed to reflect a crossover from a 3D to a 2D vortex structure. The inset shows an example of the more symmetric line shapes observed for $B > B_{2D}$, here at a temperature of 5 K and an applied field of 401 mT.

shape a truncation of the high-field tail, the line shape is quite different from that observed above the irreversibility line [see Fig. 1(b)]. Furthermore, in contrast to the low-field transition at T_m, the transition involves only a change of *magnitude* of α, not of sign. Observations of similar high-field line shapes were taken by Ref. [20] to indicate the presence of a 2D array of fluxons disordered along the c direction by random pinning. Since at low fields we have clear evidence for the existence of a *three dimensional* vortex structure, this strongly suggests that the associated transition, indicated by the change of μ^+SR line shape, is associated with a transition from a 3D to a 2D flux structure. Such a "crossover" field is expected for a highly anisotropic system such as BSCCO, and may be estimated as that field where the average intervortex distance $R_{av}\approx(\Phi_0/B)^{1/2}$ becomes less than or comparable to the Josephson length $R_J\approx\gamma s$, where s is the separation of the superconducting layers and $\gamma=(m_c/m_{ab})^{1/2}$ (m_{ab} and m_c are the components of the anisotropic effective-mass tensor parallel and perpendicular to the ab plane, respectively) [8]. Taking $s\sim15$ Å and $\gamma=150$ [8,23] yields $B_{2D}\approx\Phi_0/(\gamma s)^2\sim40$ mT. In the present data the onset of the change of flux structure is $B_{2D}\sim50$ mT, which is in accordance with the above estimate for a crossover field. Further evidence for a dimensional crossover comes from the temperature dependence of $\langle(\Delta B)^2\rangle$ above and below B_{2D}. At fields below B_{2D} the temperature dependence is anomalous only above T_m [see Fig. 2(b)], while above B_{2D} the temperature dependence is anomalous across the whole temperature range, both above and below the transition temperature T_m [18]. This may reflect the increased importance of thermal fluctuations in the more weakly coupled layers [24]. We note that our microscopic observation of a crossover field is in accordance with recent bulk-magnetization experiments [5]. Hence, to further identify our T_m with the flux-lattice melting temperature, we choose to fit the three lowest field points in Fig. 3 ($B < B_{2D}$) to the 3D melting function [6,7,10]:

$$B_m^{3D}\approx\frac{1}{[4(\sqrt{2}-1)+1]^2\pi\mu_0^2}\left(\frac{\Phi_0^5 c_L^4}{(k_B T_c)^2\lambda_{ab}^4(0)\gamma^2}\right)\times\left(\frac{1-t^n}{t}\right)^2, \qquad (2)$$

where $\lambda_{ab}(0)$ is the low-temperature superconducting penetration depth in the ab planes, n and t are as defined in Eq. (1), and c_L is the Lindemann number, which is a constant ~0.1. In order to evaluate Eq. (2) a value of the penetration depth λ_{ab} is required; an analysis of our μ^+SR line shapes at lower applied fields yields a value of around $\lambda_{ab}\approx1800$ Å. This is in agreement with a recent detailed analysis of line shapes in powder samples which gave a value of $\lambda_{ab}\approx1850$ Å [25], and values obtained from reversible magnetization measurements of $\lambda_{ab}=1500\pm300$ Å [26]. A more detailed analysis of our line shapes will be published elsewhere [27]. For the fit of Eq. (2) to the data we used $n=3.3$ [see Fig. 2(b)], $c_L\approx0.20$ [11], and a value $\lambda_{ab}\approx1800$ Å, yielding a value of the anisotropy ratio $\gamma=156$. The corresponding estimate of $B_{2D}\sim40$ mT is in reasonable agreement with our other estimate of $B_{2D}\sim50$ mT given above.

Below T_m we have observed line shapes arising from a 3D flux structure which undergoes a sharp transition at T_m to a state which is clearly different. The loss of the high-field tail for line shapes above T_m may result from a motion of the vortices or from a reduced dimensionality. However, the sharpness of the transition with temperature, the field dependence of T_m, and the closeness of the transition to the irreversibility line all justify the identification of T_m with the flux-lattice melting temperature. A transition to a vortex liquid may itself be associated with a reduction of the dimensionality, since in a 3D flux-line liquid the lines might "wiggle" along the c direction. In the liquid state the shear modulus c_{66} is zero and the tilt modulus c_{44} may allow sufficient wandering of flux lines within a distance λ_{ab} in the c direction to change the line shape substantially. The transitions from the 3D state ($T < T_m$, $B < B_{2D}$) with temperature and field are clearly different processes, since the former involves a change of *sign* of the parameter α, while the latter involves only a change of magnitude. Furthermore, the transition at T_m, which involves a change of sign of α, is observed at fields both below and above [19] the crossover field B_{2D}.

In conclusion, we have observed transitions in the flux vortex structure as a function of both field and temperature. The field dependent change is strongly indicative of a dimensional crossover from a 3D to a 2D vortex structure, while the changes associated with the temperature transition are consistent with flux-lattice melting. The μ^+SR technique has been shown to be a unique *microscopic* probe of these flux structures and transitions, being able to access regions of the phase diagram well below the irreversibility line, not accessible by transport measurements. Our conclusions concerning both the melting line and the dimensional crossover have received strong confirmation from recent neutron scattering observations by some of us of the flux-line lattice in this material [28]. We note that the μ^+SR technique yields additional microscopic information about the internal flux structures for fields $B > B_{2D}$ and temperatures $T > T_m$, both of which are regions of the phase diagram where the neutron intensity is unobservably small.

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