Longitudinal disordering of vortex lattices in anisotropic superconductors

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Vortex disordering in superconducting crystals is shown to be markedly sensitive to penetration-depth anisotropy. At low temperature and high magnetic field, the muon-spin-rotation spectra for the highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ material are found to be anomalously narrow and symmetric about the applied field, in a manner consistent with a layered vortex sublattice structure with pinning-induced misalignment between layers. In contrast, spectra for the less-anisotropic $YBa_2Cu_3O_{7-\delta}$ compounds taken at comparable fields are broader and asymmetric, showing that the vortex lattices are aligned parallel to the applied-field direction.

Recent work on highly anisotropic, or layered, cuprate superconductors has suggested the remarkable tendency toward interlayer disordering of vortex lattices in strong magnetic fields.[1] Some form of longitudinal misalignment is also expected from theoretical considerations when the interlayer superconductive coupling is weak.[2–4] The effect of such phenomena on the second moment $\langle(\Delta B)^2\rangle$ of the local magnetic-field distribution $P(B)$ has recently been considered.[5,6] Since the crucial quantity here is the penetration-depth anisotropy $\gamma=\lambda_c/\lambda_{ab}$, where λ_c and λ_{ab} are the c-axis and basal-plane components, respectively, it is instructive to compare systems having markedly different γ values. The present work takes advantage of Fourier-transform muon-spin-rotation (μSR) spectroscopy to reveal the differences between $YBa_2Cu_3O_{7-\delta}$, where $\gamma \gtrsim 5$, and $Bi_2Sr_2CaCu_2O_{8+\delta}$, where $\gamma \approx 100$.[7,8] It is shown that a layered vortex-sublattice structure, with pinning-induced misalignment between layers, is necessary to account for the very narrow and symmetric μSR spectrum in $Bi_2Sr_2CaCu_2O_{8+\delta}$ at low temperature and high magnetic field. Such a greatly attenuated local magnetic-field variation would be difficult to detect using other techniques, e.g., neutron diffraction and lattice decoration. In the present study, we consider only low temperatures, where dynamical vortex-line motion is suppressed.[9]

For large γ, vortices may be decomposed into elementary two-dimensional (2D) fluxons in individual layers (2D "pancake" vortices[10]). The magnetic interactions between 2D fluxons in neighboring layers are attenuated by a factor $d/\lambda_{ab}\sim 10^{-2}$, where d is the spacing between layers (15 Å for $Bi_2Sr_2CaCu_2O_{8+\delta}$), compared to interactions within a layer. Thus, in moderately strong magnetic fields ($H_{c1} \ll H \ll H_{c2}$), where intervortex spacings are much smaller than λ_{ab}, pinning forces could prevent interlayer alignment.

Random pinning in a vortex lattice has previously been thought to increase the μSR linewidth, e.g., via convolution with a Gaussian distribution of some width Δ.[11,12] The resulting width exceeds the theoretical width $\langle(\Delta B)^2\rangle^{1/2}$ for triangular lattices, which at an average induction $\langle B\rangle=15$ kG is given by $\sigma_{\rm tri} \approx 0.77(\phi_0/4\pi\lambda_{ab}^2)$.[11] To explain narrower widths, 2D fluxon models have been considered, where it was noted that certain superlattice arrangements could yield very small widths.[6] For 2D fluxons randomly distributed in the a-b directions, the width is predicted to be $\sigma_{\rm rand}=(\phi_0\langle B\rangle d/8\pi\lambda_{ab}^3)^{1/2}$, which in strong magnetic fields is again larger than $\sigma_{\rm tri}$.[6] The calculation for 2D triangular lattices within the layers and no alignment or correlation between the layers gives the result $\sigma_{2D}=1/4(d/a)^{1/2}\sigma_{\rm tri}$, where a is the intralayer spacing between fluxons.[5] Taking $\lambda_{ab}=2500$ Å and $a=400$ Å (for $B=15$ kG), the values for the calculated widths are $\sigma_{\rm rand}=45$ G, $\sigma_{\rm tri}=20$ G, and $\sigma_{2D}=5.5$ G. It is shown below that the $P(B)$ spectrum corresponding to σ_{2D} is appropriate for $Bi_2Sr_2CaCu_2O_{8+\delta}$.

One calculates the local field produced by a triangular lattice of 2D fluxons in a layer at height z from the expression

$$B_z(\mathbf{r})=\sum_{\mathbf{g}} h_g(z)\cos(\mathbf{g}\cdot\mathbf{r}) , \quad (1)$$

where $\mathbf{r}$ is a vector defining the observation point and $\mathbf{g}$ are reciprocal-lattice vectors. Since the depolarization of the μ^+ ensemble is sensitive mainly to the component of the local magnetic field along $\mathbf{H}$, taken to be the z direction along $\mathbf{c}$, one can ignore the discreteness along z and take the μ^+ site to be at $z=0$. In moderately strong magnetic fields ($g\lambda_{ab} \gg 1$, $g \neq 0$), the form factor can be written as

$$h_g(z) \approx \langle B \rangle (d/2G\lambda_{ab}^2) \exp[-Gz - g^2\xi_{ab}^2/2] , \qquad (2)$$

where $G \equiv (g^2+\lambda_{ab}^{-2})^{1/2}$ and $\xi_{ab} \sim 15$ Å is the coherence length in the a-b plane.[6,10] The spectral distribution in B is then computed by summing the contributions from all layers and taking a random distribution in sublattice displacements. Disorder within the layers is modeled by smearing the result with a Gaussian of width Δ.

The $YBa_2Cu_3O_7$ crystals (4 mm^2 by 0.1 mm) for this work were grown in a Cu-O flux, post-annealed in oxygen for 4 weeks, and had T_c near 90 K and $\lambda_{ab}=1400$ Å.[13,14] oxygen-reduced $YBa_2Cu_3O_{6.7}$ crystals with T_c near 60 K were also prepared. The $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals (9 mm^2 by 0.05 mm) were grown by directional solidification of a stoichiometric melt and had $T_c=90$ K, with no further heat treatment.[15] All crystals were checked for bulk superconductivity by magnetic susceptibility. Layers of crystals with the c axes aligned and a-b random were mounted with vacuum grease on heat sinks of Al, MnF_2, or fused SiO_2. Vortex states were induced by cooling in constant **H** applied either parallel to the crystal **c** axis or inclined at 45°. The μSR data were taken with a 4.2-MeV μ^+ beam at the TRIUMF cyclotron using standard time-differential detection of the emitted decay positrons. The relaxation function was multiplied by a Gaussian-decay envelope and then cosine Fourier transformed to yield $P(B)$. This procedure smoothly truncates the time domain and fixes an instrumental resolution of 2.7–5.6 G. The external field H was stabilized to a precision of 50 ppm and determined to an accuracy of 0.5 Oe from the μ^+ precession frequency above T_c. For the $YBa_2Cu_3O_7$ and $YBa_2Cu_3O_{6.7}$ samples, the background precession signal was also used to confirm H below T_c.

Figure 1 shows Fourier-transform μSR spectra obtained for $YBa_2Cu_3O_7$ at 7 K for two orientations of magnetic field. A background signal from 10-ppm-purity Al has been subtracted. The μSR line narrows and shifts in a tilted field, in accordance with the known anisotropy $\gamma=5$. The curves show fits for theoretical local magnetic-field distributions in triangular vortex lattices,[16] convolved with Gaussian broadening to account for the instrumental resolution and flux-line pinning.[11] The random inhomogeneity in the local field is expressed by a width parameter Δ, which contributes 5% or less to the overall width. The quantities varied in the fit are λ_{ab}, the average magnetic induction $\langle B \rangle$, and Δ. The dashed lines in Fig. 1 show the position of the external field, $H=11\,020$ Oe, which was established independently of the fit, $\langle B \rangle = 11\,026$ G. The small difference between $\langle B \rangle$ and μH is consistent with flux pinning and demagnetization in thin crystals.[17] The shift of $+6$ G indicated by the fit appears to be within the uncertainty represented by Δ. However, it may also indicate some longitudinal disorder in the vortex lattice, which is discussed further in connection with the results for $Bi_2Sr_2CaCu_2O_{8+\delta}$. Qualitatively similar results were obtained for

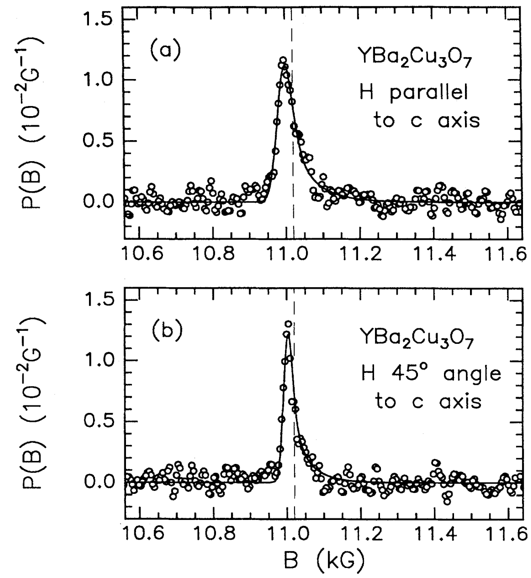

FIG. 1. Fourier-transform μSR spectra (points) at 7 K for an ensemble of $YBa_2Cu_3O_7$ crystals with external magnetic fields H (marked by dashed lines) applied (a) parallel to the **c** axis or (b) inclined at a 45° angle. Curves are fits for penetration depth $\lambda_{ab}=1490$ Å, $\lambda_c/\lambda_{ab}=5$, and random broadening $\Delta=18$ G for (a) and $\Delta=9$ G for (b). Instrumental resolution width is 5.6 G.

$YBa_2Cu_3O_{6.7}$ crystals (see Fig. 2), showing a comparatively more narrow distribution as a consequence of the larger λ_{ab}.[14] The prominent feature clearly displayed by $P(B)$ in both Figs. 1 and 2 is that the maxima, i.e., the smeared-out van Hove singularities, are displaced significantly below $\langle B \rangle$. We therefore conclude that pinning in $YBa_2Cu_3O_{7-\delta}$ produces relatively minor deviations from the $P(B)$ spectra expected for ideal triangular vortex lattices.

For $Bi_2Sr_2CaCu_2O_{8+\delta}$, crystals, an asymmetric line shape is observed only at low magnetic fields ($H \lesssim 5$ kOe).[18] At high magnetic field ($H=15$ kOe), on the oth-

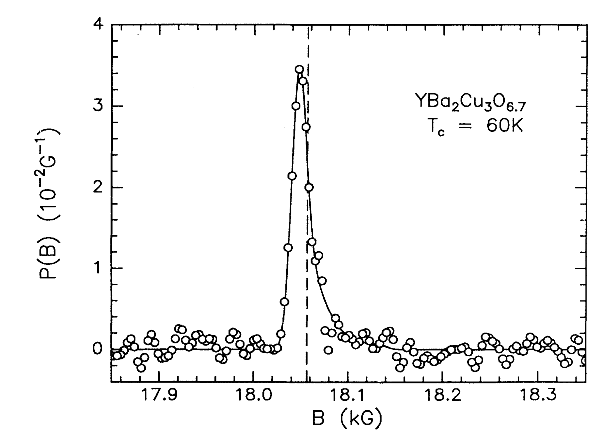

FIG. 2. Spectrum for $YBa_2Cu_3O_{6.7}$ crystals at 7 K with H (marked by dashed line) along the **c** direction. Curve is a fit for $\lambda_{ab}=2580$ Å.

er hand, $P(B)$ takes on a qualitatively new form of a substantially narrowed, nearly symmetric peak centered on μH.[18] Therefore the intrinsic value $\lambda_{ab}=2500$ Å for $Bi_2Sr_2CaCu_2O_{8+\delta}$, taken for the theoretical calculations above, is not known accurately. We obtain a rough estimate of 3100 Å from the μSR linewidth at low temperature and field, but this is an upper limit, as it is uncorrected for fluxon-lattice disorder. In principle, one may determine λ_{ab} from the magnetization $M=-(\phi_0/32\pi^2\lambda_{ab}^2)\ln(\alpha H_{c2}/H)$, where $\alpha\approx 0.4$, although it is also perturbed by pinning. Using the diamagnetic shift in the muon local field, found to be -3.4 G at $H=300$ Oe, this method yields a result between 2100 and 2900 Å, with the uncertainty arising from the demagnetization corrections. Various values from 1700 to 3000 Å were obtained from measurements of $dM/d\ln(H)$ by several groups.[19]

Figure 3 shows data for $Bi_2Sr_2CaCu_2O_{8+\delta}$ obtained by field cooling to $T=6$ K in moderately high field $H=15\,049$ Oe (dashed line) applied along the **c** axis and determined (± 1 Oe) from measurements above T_c. In addition to a smaller linewidth compared to the results for $YBa_3Cu_3O_{7-\delta}$ (note scale changes), the spectrum for $Bi_2Sr_2CaCu_2O_{8+\delta}$ appears more symmetric and is *unshifted* with respect to $|\mathbf{H}|$. This effect is not due to motion, since the vortex lattice should be well below its freezing temperature.[20] Instrumental background contributes 3% or less to this spectrum.

To illustrate the disagreement with the prediction for a triangular lattice of line vortices, a dotted curve in Fig. 3 shows the calculation for our estimated $\lambda_{ab}=2500$ Å. In general, the characteristic asymmetry in $P(B)$ is largely preserved when the fluxons form continuous vortex lines. Moderate disorder in a triangular lattice of straight vortices, e.g., random displacements on the order of $0.1a$ in the a-b plane, where a is the intervortex spacing, broadens, but has little effect on the location of the maximum in $P(B)$. Similarly small random displacements of vortex-core positions from one layer to the next broaden the effective core radius and truncate the high-field tail of $P(B)$. In order to explain both a narrow linewidth and a maximum close to $\langle B\rangle$, one needs to consider substantial reconstruction or disordering of the vortices along the **c**-axis direction. Since flux pinning is observed in $Bi_2Sr_3CaCu_2O_{8+\delta}$ at low temperatures,[9,21,22] it will be assumed that the disorder is stabilized by pinning and that thermal vibrations and motional narrowing may be neglected at low temperature.

The solid curve in Fig. 3 was calculated with our model of 2D fluxon lattices arranged in layers, with no interlayer alignment or correlation. Broadening by instrumental resolution and nuclear dipolar fields have been included. The results of the fit are $\lambda_{ab}=2500\pm 350$ Å, $\Delta\approx 3$ G, and $\langle B\rangle=15\,050.4\pm 0.5$ G, which agrees with μH to within the experimental accuracy. Short-range correlation in the relative displacement between layers can be estimated with this model by scaling the calculation of $P(B)$ and by substituting a larger interlayer spacing, $d'>d$ and a smaller $\lambda'_{ab}=\lambda_{ab}(d/d')^{1/2}$. The upper limit $\lambda_{ab}\leq 3100$ Å, as ascertained earlier, imposes the constraint $d'\leq 30$ Å. This suggests that the sublattice

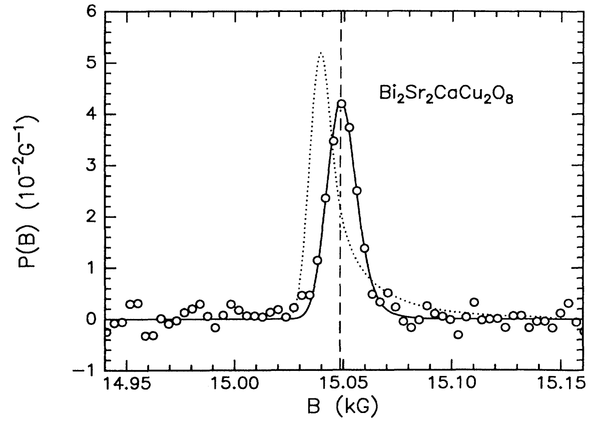

FIG. 3. Spectrum for $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals with H (dashed line) along **c**. Solid curve is a fit using a disordered 2D fluxon model. The dotted curve is for a perfect triangular lattice. $\lambda_{ab}=2500$ Å for both curves.

layers are essentially uncorrelated. The width of the experimental spectrum is about 7.3 G, as estimated from the second moment, after correcting for instrumental width (2.7 G) and nuclear dipolar broadening (2.9 G). The net width is close to our estimate of $\sigma_{2D}=5.5$ G. Generally, more correlation between layers or less correlation inside the sublattices would necessarily give a larger linewidth. These results show that the local magnetic-field distribution computed from this model is in good agreement with the μSR experiment. We should remark that we have not relied on the scaling of σ_{2D} with $\langle B\rangle^{1/4}$ prediced by the model, since the weak field dependence might be concealed by a changing correlation between sublattices as $\langle B\rangle$ is changed. Moreover, the highest field presented here was limited by the criterion $H \ll H_{c2}$, to minimize the finite-core corrections.[11]

In conclusion, the narrow unshifted peak in the Fourier-transform μSR spectra for $Bi_2Sr_3CaCu_2O_{8+\delta}$ crystals has been quantified in terms of interlayer disordering of the vortex lattice along the direction of the applied field. The result shows that the vortex structure is extrinsically controlled by random pinning forces rather than by interlayer coupling when the latter is weak. In contrast, the spectra for $YBa_2Cu_3O_7$ and $YBa_2Cu_3O_{6.7}$ crystals are well described by triangular lattices of continuous vortex lines, having relatively minor amounts of disorder.

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