Observations of Suppression of Static and Dynamic Disorder in $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ Crystals by Columnar Defects

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Muon spin rotation and small angle neutron scattering measurements have been carried out on $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ single crystals irradiated with fast heavy ions. The data give substantial evidence that even below the matching field, the positions of the vortices, in a plane perpendicular to the tracks, are not random. Furthermore, the crossover to a glassy vortex arrangement, observed in the pristine material, is moved to higher fields. It is shown that the presence of the columnar defects also strongly suppresses the thermal fluctuations of the vortices in comparison with the pristine material. [S0031-9007(98)07796-5]

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The magnetic behavior of high-T_c superconductors is strongly influenced by static (pinning induced) and dynamic (thermal) disorder [1], due to both the large superconducting anisotropy γ and the high value of the Ginzburg-Landau parameter κ. The irradiation of samples with heavy ions, so as to create cylindrical damage tracks through the sample, provides one way to artificially introduce anisotropic pinning [2]. This is particularly effective at fields below the matching field B_Φ, which is the field at which the number of flux lines equals the number of these columnar defects (CD). In the highly anisotropic system $Bi_{2.15}Sr_{1.85}Ca_1Cu_2O_{8+\delta}$ (BSCCO), the vortices may exhibit strong quasi-two-dimensional (2D) behavior in the pristine material [3–7]. This brings into question the effectiveness of anisotropic pinning, since if the vortices behave as very weakly coupled 2D "pancake" vortices, then the system may exhibit an *isotropic* response as the vortices become pinned onto the CD irrespective of the field direction [8]. In BSCCO, transport and magnetization measurements suggest an isotropic response at low temperatures crossing over to anisotropic behavior at higher temperatures [8,9], although this may arise from a change in vortex dynamics [10]. In this Letter we use the technique of muon spin rotation (μSR) to investigate the vortex behavior in irradiated BSCCO on a microscopic scale via measurements of the local field distribution of the *equilibrium* vortex state. These measurements are complemented by small angle neutron scattering (SANS) measurements which give additional information concerning the spatial distribution of the internal field.

The crystals were grown using a floating zone technique as described elsewhere [11], and the sample consisted of a mosaic of crystals of typical dimension 5 mm $\times$ 3 mm $\times$ 400 μm. The irradiation was carried out at GSI (Darmstadt, Germany) using 17.7 GeV U ions, which experience an estimated energy loss in the crystals of 25 keV/nm. This high energy was chosen so as to enable the ions to produce damage tracks which extend throughout the crystal. The penetration was checked by placing a monitor behind the thickest crystal to record the transmitted flux. The incoming beam was monitored using an ionization chamber, and the ion beam scanned across the sample to produce a uniform illumination. The irradiation was such that the resulting tracks were oriented either parallel or at 45° to the crystallographic c axis, with a density equivalent to $B_\Phi = 100$ mT.

The neutron measurements were carried out at the Institut Laue Langevin (ILL), Grenoble, France, using instrument D11 and an arrangement similar to that described in Refs. [12,13]. The μSR experiments were carried out on beam line πM3 at the Paul Scherrer Institute (PSI), Switzerland, and at the ISIS MUSR facility at the Rutherford Appleton Laboratory (RAL), U.K., using experimental arrangements as described in Refs. [5,14] (PSI) and Ref. [15] (RAL). The samples were backed by a Fe_2O_3 plate, to rapidly depolarize, outside of the observable time window, any muons not hitting the sample. In a μSR experiment, spin-polarized muons are introduced into the sample, which is mounted in a magnetic field applied perpendicular to the muon spin. The muon spins then precess in the local internal field of the mixed state of the superconductor. From the distribution of these precession frequencies, which we observe by detecting positrons emitted in the anisotropic decay of the muon, the field probability distribution $p(B)$ can be determined [16]. For a conventional vortex-line lattice, $p(B)$ has a highly

characteristic form, so the presence of a linelike lattice is easily detectable [3,7,16]. The shape of $p(B)$ is highly asymmetric with a tail extending to fields above the average, due to muons stopping in or near the narrow vortex cores [16]. This high-field tail will also be present when a vortex line is pinned to a columnar defect, but the line shape will be influenced by the disorder introduced into the vortex lattice by the presence of the columnar defects. For the case of perfect pinning and a field equal to B_Φ, with each vortex trapped by a defect, the positions of the vortices would be random in a plane perpendicular to the applied field. This case has been treated in Ref. [17], where an increased weighting at lower fields is predicted, resulting in a less asymmetric line shape.

It is useful to quantify the degree of asymmetry of the μSR line shape, for which we use a dimensionless parameter $\alpha = \langle \Delta B^3 \rangle^{1/3} / \langle \Delta B^2 \rangle^{1/2}$ derived from the second and third moments of the measured field distribution [3,5–7]. For an ideal flux line lattice, numerical simulations predict a value of $\alpha \simeq 1.2$ for our experimental arrangement. For a truly random arrangement of vortices, the width of the distribution, given by the second moment, would be very much greater than for the perfect lattice [17]. The linewidths measured on the irradiated samples are, in fact, significantly smaller than predicted for the random case, indicating that there exists *some degree of positional correlation* between vortices in a plane perpendicular to the field. This is in accord with recent simulations [18] and SANS experiments, as discussed elsewhere [13]. These correlations are believed to originate from two sources: first, a random distribution of defects will naturally contain some areas where they are closely spaced, such that vortex-vortex interactions will make it energetically unfavorable for all of them to be occupied, even at B_Φ. Second, for a sample cooled in an applied field at which vortex-vortex interactions are significant (strongly overlapping vortices) at the depinning temperature, the vortices will already be correlated as they enter the irreversible region. As they become localized onto tracks, significant vortex-vortex correlations are thus frozen in [19]. For a typical simulated arrangement of flux lines in irradiated samples given in Ref. [18], we would expect to measure $\alpha \simeq 1$ for our experimental arrangement. Figure 1 shows the field dependence of α at a temperature of 5 K for an irradiated sample, with the tracks parallel to the c axis, and for a pristine sample, both with the field directed along the c direction. In the irradiated material, for fields up to more than twice B_Φ, the measured value of $\alpha \simeq 1$. This reflects the existence of a high-field tail in the probability distribution, which is symptomatic of a high degree of order along the field direction. That is, *the vortex lines are straight* even though not all of them are pinned to CD. In contrast, for the pristine sample α drops to a value of $\alpha \simeq 0.5$ at the crossover field $B_{cr} \sim \Phi_0 / \lambda_{ab}^2 = 65$ mT [3,6], above which some entangled glassy vortex phase is believed to exist [3,6,20,21]. In the irradiated samples
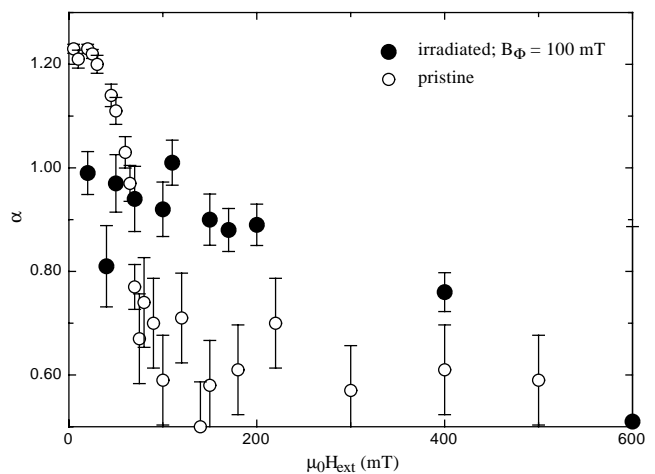

FIG. 1. Field dependence of the μSR line shape asymmetry parameter $\alpha = \langle \Delta B^3 \rangle^{1/3} / \langle \Delta B^2 \rangle^{1/2}$ for a pristine sample (taken from Ref. [6]) and an irradiated sample having a matching field $B_\Phi = 100$ mT (see text). The reduction of α indicates a more symmetric line shape, due to a reduction of the high-field tail in the field distribution, which arises from regions close to the vortex cores. A fall in α suggests that the vortices are less straight (see text). In the pristine material this occurs above the vortex disorder crossover $B_{cr} \sim 65$ mT, whereas in the irradiated sample this change is shifted to much higher fields.

there is thus a suppression of the onset of the disordered vortex-glass phase due to the presence of the CD. At fields greater than B_Φ, those vortices pinned on tracks will create a linear potential "cage" for the interstitial vortices [22], thus sustaining the correlations along the track direction. The field above which this disorder is no longer suppressed has been estimated as $B \gtrsim B_\Phi^2 / B_{cr}$ [19], which in our sample yields $\sim$150 mT, in reasonable agreement with the very broad crossover observed (Fig. 1). We note, however, that the analysis of Ref. [19] assumes a strongly Josephson coupled system, which may not be appropriate for BSCCO [7,23].

The dynamic disorder of the vortex system is also readily observable using μSR [5]. It has been shown in Refs. [5,24] that fluctuations of pancake vortices lead to a reduction in the width of the field distribution measured by μSR according to a Debye-Waller factor,

$$\langle \Delta B^2 \rangle (T) = B^2 \sum_{\tau \neq 0} \frac{e^{-\tau^2 \langle u^2 \rangle / 2}}{[1 + \lambda^2(T) \tau^2]^2}, \qquad (1)$$

where $\langle u^2 \rangle$ is the mean square displacement of vortices from their average positions. For the case of a conventional vortex lattice of static, rigid flux lines ($\langle u^2 \rangle = 0$), evaluation of Eq. (1) yields a temperature dependence of $\langle \Delta B^2(T) \rangle$ which is *field independent* for $B_{c_2} \gg B > B_{c_1}$. Thus by measuring the effect of field on the temperature dependence of the μSR linewidth, it is possible to obtain information on the dynamic fluctuations of the vortices. This was demonstrated in Refs. [5,7], where $\langle \Delta B^2 \rangle^{1/2}(T)$ was measured in unirradiated BSSCO crystals for a range

of fields applied parallel to the c direction, and was found to exhibit a *strong field dependence*. As the field is increased, the effects of vortex fluctuations become more pronounced, since $\langle u^2 \rangle^{1/2}$ increases relative to the intervortex distance. We now consider samples which have been irradiated parallel to the c direction to produce CD with a matching field of 100 mT. In Fig. 2 are measurements of $\langle \Delta B^2 \rangle^{1/2}(T)$ for a range of fields applied parallel to the c direction. The temperature dependence for this sample is *independent* of the value of the applied field within the uncertainties of the measurement, which is in stark contrast to the results from the pristine material [5,7]. This implies a strong suppression of the dynamic vortex fluctuations due to the strong pinning of the vortices by the CD [1,2,8–10,19]. To complement the μSR results we also performed SANS measurements on the same crystals. For something approaching an ideal vortex-line lattice, SANS experiments give rise to a Bragg diffraction pattern, as measured for BSCCO in Ref. [4]. However, in such a highly disordered system of vortices as a Bose-glass phase induced by CD [2], the scattered neutron intensity is given by a convolution of the pair correlation function $S(\tau)$ of the vortex positions and the square of the form factor of a single flux line $f(\tau) = B[1 + \lambda^2(T)\tau^2]^{-1}$ [13]. If the positions of the vortices are truly random, then the scattered neutron intensity $I(q) \propto f^2(\tau)$, and will not contain any structure. As discussed above, however, there exist some residual vortex-vortex correlations, giving a small contribution to $I(\tau)$ from an $S(\tau)$ peaked at $\tau \sim 2\pi\sqrt{B/\Phi_0}$, although the data are effectively dominated by $f(\tau)$ [13]. Thus theo-

retically the neutron scattered intensity integrated over all wave vectors τ, like the μSR linewidth, depends on $f^2(\tau)$, which in principle could similarly be modified by a Debye-Waller type correction to account for thermal fluctuations of the vortices [compare to Eq. (1)]. We should thus expect the square root of the integrated intensity $I^{1/2}(T)$ to vary in a similar manner to $\langle \Delta B^2 \rangle^{1/2}(T)$. In Fig. 2 $I^{1/2}(T)$ is plotted alongside $\langle \Delta B^2 \rangle^{1/2}(T)$ for a range of applied fields. The background contribution to the scattered intensity has been removed by subtraction of the signal taken in the normal state. The temperature variation of $I^{1/2}(T)$ is in good agreement with the muon data, and further reinforces the *field independence* of the measurements [4,13]. This absence of any significant Debye-Waller type contribution thus implies a suppression of thermal fluctuations due to the presence of the columnar defects. The temperature variation may thus reasonably be assumed to be a true reflection of the *intrinsic* behavior of the penetration depth, as given by Eq. (1). It is interesting to note that $\langle \Delta B^2 \rangle^{1/2}(T)$ is linear in T, within the uncertainty, below approximately 50 K, which has previously been interpreted as evidence for d-wave coupling in μSR measurements on YBa$_2$Cu$_3$O$_x$ [25].

From the second set of samples with the irradiation at 45° to the c axis we were able to investigate the angular dependence of the anisotropic pinning. The field was applied either parallel to, or perpendicular to, the tracks, while maintaining the fields at 45° to the c axis in both cases. The results are shown in Fig. 3, where the temperature dependence of the μSR linewidth is shown for both orientations at an applied field of 45 mT. For comparison we also include 50 mT μSR and SANS data taken from the measurements on samples irradiated parallel to c. Interestingly, the curves for the 45° samples are identical, irrespective of whether the field is parallel or perpendicular to the tracks. This implies that the degree to which thermal fluctuations are suppressed by the defects, an indirect measure of the pinning strength, *does not depend greatly on the orientation of the field to the tracks*. This is in agreement with recent magnetization studies [10] which show that the zero temperature pinning strength is isotropic, even in the reversible region where anisotropic pinning properties have been reported [8,26]. This apparent contradiction may be understood by attributing the apparent crossover from isotropic to anisotropic pinning properties at high temperature to a change in dynamics which occurs when the activation of vortex strings, not pancakes, becomes responsible for vortex motion [10]. The strings of pancakes are more effectively pinned by the extended defects. It is noteworthy that we measure the *equilibrium* vortex structure, and deduce an *isotropic* pinning strength at all temperatures, in accord with the conclusions of Ref. [10]. The degree of *straightness* of the vortex lines, however, which is measured by the μSR asymmetry parameter α, is found to be quite different. At low temperatures, for the fields parallel
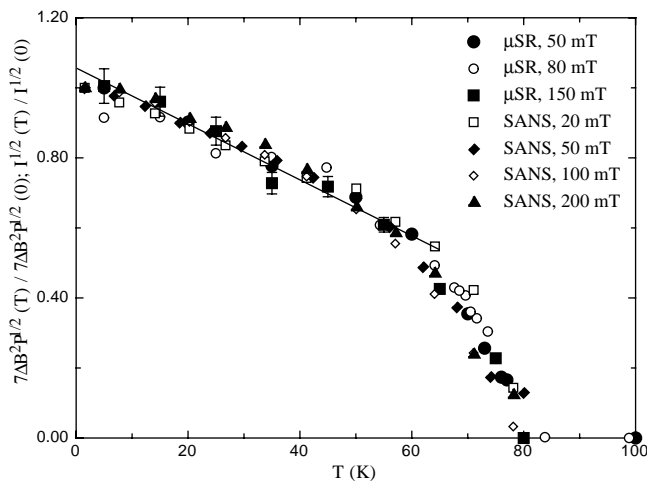

FIG. 2. The normalized temperature dependence of the μSR linewidth $\langle \Delta B^2 \rangle^{1/2}(T)/\langle \Delta B^2 \rangle^{1/2}(0)$ for several applied fields in a BSCCO sample with columnar defects ($B_\Phi = 100$ mT) parallel to the c axis. Also shown for several applied fields is the normalized square root of the SANS signal intensity $I^{1/2}(T)/I^{1/2}(0)$, where $I(T)$ has been integrated over the full wave vector range of the experiment $\tau \sim 10^{-3}$–1.2×10^{-2} Å^{-1}, and should be closely related to the μSR linewidth (see text).
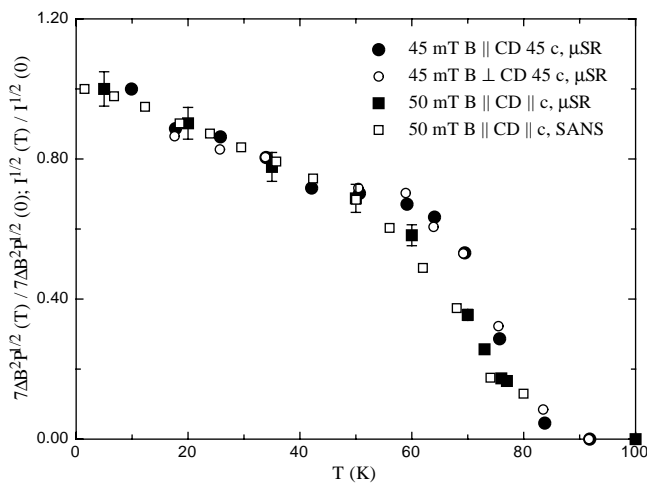
FIG. 3. The normalized temperature dependence of the μSR linewidth for the sample with the columnar defects at 45° to the c axis ($B_\Phi = 100$ mT), where a field of 45 mT is applied both parallel and perpendicular to the tracks. Also shown is the temperature dependence of the μSR linewidth and the integrated SANS intensity from the sample with the same matching field, but having the defects parallel to the c axis. In that case the field was 50 mT applied parallel to the tracks. For the 45° sample, the temperature dependence is identical for both orientations, implying the pinning strength is similar in both cases.

to the tracks at 45° to c, $\alpha \simeq 0.8$, which is close to that obtained for tracks parallel to c, $\alpha \simeq 1$. Thus we conclude that *the vortex lines are relatively straight.* For the fields perpendicular to the tracks at 45° to c, however, $\alpha \simeq 0.4$, which is similar to the value obtained in the pristine sample above the disorder crossover B_{cr} [6]. In the pristine material the angular variation from the c direction of $B_{cr}(\theta) \approx B_{cr}(0)/\cos(\theta)$ [14], so the effective $B_{cr}(45°) \approx 92$ mT is well above the applied field. From this we deduce that, *due to the columnar defects,* for this orientation the vortex lines are relatively disordered along their length. As discussed in Ref. [8], at low temperatures it is likely that the average flux line direction follows that of the applied field for all orientations. One possibility for the perpendicular orientation is that for part of their length the flux lines accommodate to the tracks, producing a zigzag pattern (the "totally adjusted" arrangement of [8]). An alternative scenario, however, is that the flux lines simply meander along their length since individual pancakes respond to the tracks as a source of uncorrelated disorder (point defects), forming a "vortex-glass" phase, as observed on the pristine material above B_{cr} [6]. At higher temperatures (>70 K) the value of $\alpha \approx 0.5$, irrespective of the angle of the applied field, indicating that due to thermal delocalization, the *pancake distribution in the reversible state does not depend on the orientation of the field.* This is in accord with recent magnetization measurements which suggest that the vortex distribution in the reversible regime depends only on the magnitude of the component of the field along the c direction [10]. There

is, furthermore, a significant wandering of the flux lines along their length, indicated by the low value of $\alpha \approx 0.5$.

In conclusion, we have studied the effects of the introduction of CD into the highly anisotropic superconductor BSCCO, where we find a suppression of both static and dynamic disorder in the lattice due to the presence of the pinning introduced by the tracks. The pinning strength appears not to depend strongly on the angle of the field to the tracks, although the straightness of the flux lines varies significantly with orientation at low temperature. At high temperature the equilibrium vortex distribution is isotropic with respect to the field direction, which supports the view that the anisotropic pinning observed in transport measurements is a dynamic effect [8,10,26].

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