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Evidence for line vortices in $Bi_2Sr_2CaCu_2O_8$

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$Bi_2Sr_2CaCu_2O_8$ (BSCCO) crystals were irradiated with 5.8-GeV Pb ions to produce columnar defects either along the c direction or at 45° with respect to it. Magnetization curves of the irradiated BSCCO crystals were measured with the applied field at different directions relative to the defects. The width of the magnetization curves, which reflects the pinning strength, is found to be the largest for fields along the defects. This unidirectional enhancement clearly indicates the line nature of the vortices in BSCCO.

In layered high-temperature superconductors (HTS) with weak Josephson coupling between the layers, such as in $Bi_2Sr_2CaCu_2O_8$ (BSCCO), it is expected that the vortices would be in the form of a linear chain of two-dimensional (2D) pancakes mainly coupled by the Josephson currents.[1] Such vortices, although different from Abrikosov vortices, should still maintain their line features and it should be possible to tilt them by an external magnetic field. Experimental results for BSCCO showed that the formation of vortices is mainly related to $H_\perp$, the component of the field that is perpendicular to the layers, whereas the component parallel to the layers seemed to penetrate freely.[2] A possible interpretation of this experimental observation is that the CuO_2 layers are not coupled by Josephson interaction and thus the vortices are in form of 2D pancakes that are coupled only by magnetic interactions. In this case the magnetization depends *only* on $H_\perp$ and the vortices do not maintain their line features in the sense that it should not be possible to tilt them by an external magnetic field.[1] However, as was pointed out recently,[3] these experimental results[2] can also be attributed to the large anisotropy in the screening currents in BSCCO, since in this case the magnetization depends *mainly* on $H_\perp$. In this alternative interpretation there are no special assumptions about the decoupling of the CuO_2 planes or the breakdown of line feature of vortices.[3] Therefore, at this stage these experimental data are not univocal either concerning the coupling between the layers or regarding the line features of the vortices.

The purpose of this paper is to present experimental evidence for line features of vortices in BSCCO crystals. Our measurements were performed in crystals irradiated with high-energy Pb ions. In such irradiation each ion produces a continuous amorphous track, with a diameter of 5–7 nm, that crosses the crystal,[4] and the induced columnar defects serve as oriented pinning centers for the vortices. Measurements of HTS irradiated with heavy ions have been recently used for the study of the nature of the vortices.[5–8] Gerhauser *et al.*[7] report on small pinning energies in irradiated BSCCO crystals and attribute this observation to single-pancake depinning. They find that the measured pinning energy agrees quantitatively with theoretical estimates for vanishing Josephson coupling. However, this quantitative comparison suffers from uncertainty in the values of ξ_{ab} and λ_{ab},[9] and, thus, the relatively small pinning energies, which are also observed in irradiated YBCO crystals,[6] can be attributed to the low energy of kink formation,[10] with no special assumption regarding the vanishing of Josephson coupling between the layers. Thompson *et al.*[8] studied vortex features in BSCCO crystals that were irradiated at different angles relative to the c axis. They measured the magnetization curves with the applied magnetic field in various directions relative to the defects at temperatures *below* 50 K and reported on very small differences between the curves. Their interpretation was that this behavior is due to the 2D nature of BSCCO. However, we report here on apparent unidirectional pinning, particularly *above* 50 K. This clearly indicates that the vortices can be tilted away from the defects by the applied field and can thus provide an unambiguous indication of their linear nature.

Irradiation was carried out at the Grand Accelerateur National d'Ions Lourds (GANIL, Caen, France), with a beam of 5.8-GeV Pb ions at room temperature. The total fluence was 10^{11} ions/cm^2; thus there is one vortex per columnar defect at a field of 2 T, which is above our maximum field of 1.6 T. The magnetization curves were measured with the applied field at different angles ϕ with respect to the c direction. All the measurements were performed on an Oxford Instruments vibrating-sample magnetometer (VSM), which allows a rotation of the sample relative to the magnetic field. We have used two samples, namely a $1.6\times0.95\times0.046$-mm^3 crystal irradiated along the c direction and a $1.6\times0.9\times0.046\text{-mm}^3$ crystal irradiated at 45° relative to this direction. We refer to these crystals as IR0 and IR45, respectively. As a reference, we also performed measurements on an unirradiated (UIR) $1.25\times0.75\times0.07\text{-mm}^3$ sample from the same batch. Sample preparation is described in Ref. 11. The transition temperature $T_c=85$ K of the UIR samples is reduced by less than 0.5 K after irradiation.

Figure 1 shows the critical current of IR0, IR45, and UIR at $H=0.1$ T as a function of temperature. In this figure the field is along the c direction for UIR and IR0, and it is along the defect for IR45. The critical currents were measured using the Bean critical model for samples of rectangular cross section, $J_c=20\Delta M/[d_1(1-d_1/3d_2)]$, where $d_1\le d_2$ are the sides of the rectangle, and ΔM is the difference between the magnetization in the ascending and descending branches of the magnetization curves.[12] It is clear that the critical current is significantly increased after irradiation, indicating that the columnar defects are efficient pinning centers in BSCCO and that at these temperatures the intrinsic bulk pinning is negligible relative to pinning by columnar defects. Similar critical currents were reported previously for irradiated and unirradiated BSCCO crystals.[7,8]

In Fig. 2 we compare the magnetization curves of IR45 for $\phi=0°$ and $\pm45°$ at $T=60$ K. The angle ϕ is measured relative to the c axis, and $\phi=45°$ is the direction of the defects for this sample. This sample allows us to compare curves for angles $\phi=\pm45°$, which, without the columnar defects, are symmetric relative to the c axis. Thus, it is obvious that any difference between each pair of curves is due to the interaction between the vortices and the columnar defects. Note in Fig. 2, and also in Fig. 3, that the magnetization $M=m/\cos\phi$, where m is the measured magnetization and ϕ is the angle between the field and the c direction. This is done in order to correct for the fact that the VSM measures the component of the magnetization along the field, whereas the magnetization vector points in the c direction.[13] In order to compare magnetization curves with the applied field at different angles relative to the c direction, we take into account that the main response of the sample magnetization is due to $H_\perp$.[3] As discussed above, this scaling is strictly valid when the planes are not coupled by Josephson currents, but it is quite adequate also in the presence of Josephson coupling in the case of high anisotropy. Anyway, it is noteworthy that this scaling does not affect the comparison between magnetization curves taken with the field at symmetric angles relative to c (e.g., ±45°) for which the $\cos\phi$ terms have identical values.

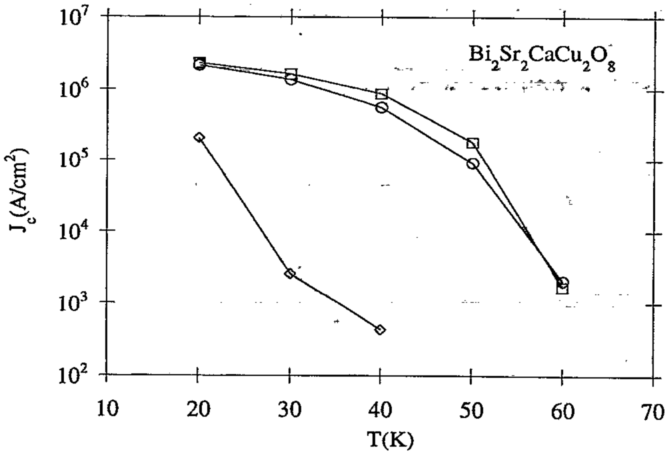

FIG. 1. The critical current density of IR0 (circles), IR45 (squares), and UIR (diamonds) at $H=0.1$ T as a function of temperature. The field is along the c direction for UIR and for IR0, and along the defect for IR45.

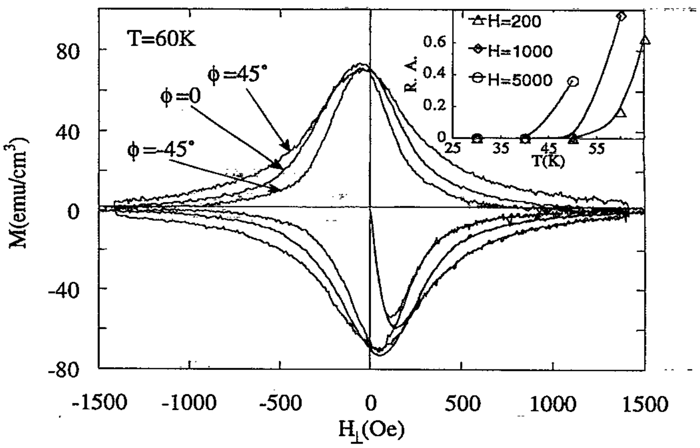

FIG. 2. Magnetization curves of IR45 at $T=60$ K, where the field is at angles $\phi=0°$ and ±45° with respect to the c direction. Note that $M=m/\cos\phi$, where m is the measured magnetization, and $H_\perp=H\cos\phi$. Inset: the temperature dependence of the relative anisotropy (RA) in IR45 at various fields.

The width of the magnetization curves of Fig. 2 demonstrates that the pinning strength is larger when the field (and the vortices) are aligned along the defects. The smaller width that is observed when the field is not along

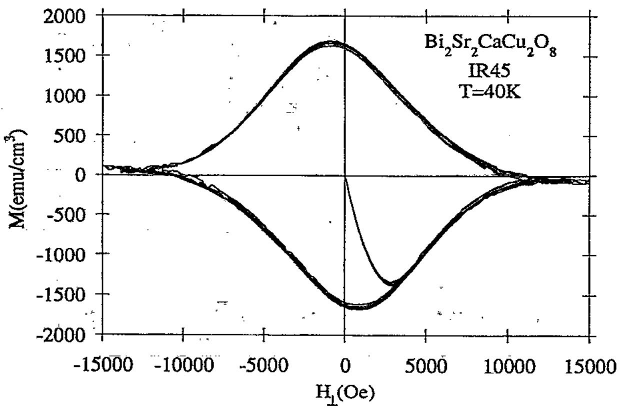

FIG. 3. Magnetization curves of IR45 at $T=40$ K, where the field is at angles $\phi=0°$, ±30°, and ±45° with respect to the c direction. Note that $M=m/\cos\phi$, where m is the measured magnetization, and $H_\perp=H\cos\phi$.

this direction indicates that in this case the vortices are not fully trapped in the columnar defects. Instead, the vortices are aligned in a direction determined by the applied field. This unidirectional pinning is clearly observed in all the numerous magnetization curves of IR0 and IR45 and is particularly pronounced at temperatures $T \geq 50$ K. As discussed above, this possibility of tilting the vortices by the external field demonstrates the intrinsic line features of the vortices. Such intrinsic line features should be observed in unirradiated samples as well. However, they are difficult to observe in the UIR sample since there are no intrinsic unidirectional defects that could give rise to such a pronounced dependence of the magnetization curves on the field direction.

It is clear that the observed unidirectional pinning excludes the previous suggestions that the magnetization depends *only* on $H_\perp$ and that the vortices behave as if they are in the form of 2D pancakes without Josephson coupling. If this were the case, then we should not have observed any difference between the magnetization curves and, in particular, when comparing symmetric angles with respect to the c axis.

A similar unidirectional pinning enhancement has recently been reported for $YBa_2Cu_3O_7$ (YBCO) crystals with columnar defects.[5,6] We note that for YBCO it is commonly accepted that the flux may be described in terms of line vortices[1,14] and a unidirectional pinning enhancement is expected. Another interesting observation that can be made from Fig. 2 is the fact that the magnetization at zero field does not depend on ϕ. Similar observations were reported for irradiated YBCO crystals and they were attributed to reorientation of vortices along the defects when the intensity of fields that were not along the defects was not sufficient to tilt the vortices away from the defects.[6]

The unidirectional pinning is much less pronounced at low temperatures. Figure 3 presents the magnetization curves at 40 K for IR45, where the applied field is at angles $\phi=0$, $\pm 30°$, and $\pm 45°$ with respect to the c direction. The main feature in this figure and in all the recorded magnetization curves of IR0 and IR45 at temperatures $T<50$ K is that magnetization curves measured with the applied field at various directions relative to the defects are almost indistinguishable. Indeed, as we mentioned above, there are previous similar reports on nearly isotropic pinning at low temperatures in BSCCO crystals irradiated by heavy ions.[8] These results were attributed to the 2D nature of BSCCO, contrary to the 3D nature of YBCO. Apparently, our results at higher temperatures are in conflict with this conclusion. Moreover, even at $T \leq 50$ K our recent preliminary measurements, with greater sensitivity, reveal that there is still unidirectional pinning, implying that the vortices also maintain their line features at lower temperatures. This last point, however, needs further study.

The inset of Fig. 2 present typical data for the temperature dependence of the relative anisotropy (RA) in IR45 at various fields. We define the RA as

$$\frac{\Delta M(\phi=45°)-\Delta M(\phi=-45°)}{\Delta M(\phi=45°)+\Delta M(\phi=-45°)}\ ,$$

where ΔM is the width of the magnetization curve for the indicated field, which is at an angle ϕ with the c axis. The RA decreases sharply below 50 K, particularly in the low-field limit. This temperature dependence of the RA may be related to other irreversible properties that change dramatically below 50 K. We see (Figs. 1–3) that in this temperature interval the pinning strength decreases significantly in the irradiated sample, and in the unirradiated sample as well. There are also many previous reports on changes in the irreversible behavior of BSCCO around, or below, 50 K. In particular, when the temperature is decreased the bulk pinning is significantly enhanced[15] and the first field for flux penetration exhibits a sharp upturn.[16] Therefore, it is plausible that the increase in the RA is related to the decrease in the irreversibility and vice versa.

In conclusion, our data yield a clear experimental observation of unidirectional pinning of vortices in BSCCO, which is consistent with the expected line features of the linear chains of pancakes. This observation emphasizes the importance of the Josephson coupling between the CuO_2 layers and excludes the interpretation of vortex properties in BSCCO in terms of decoupled 2D pancakes at the fields and temperatures where unidirectional pinning is observed.

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[1] L. N. Bulaevskii, S. V. Meshkov, and D. Feinberg, Phys. Rev. B **43**, 3728 (1991); L. N. Bulaevskii, M. Ledvij, and V. G. Kogan, *ibid.* **46**, 366 (1992); J. R. Clem, *ibid.* **43**, 7837 (1991); J. R. Clem, M. K. Coffey, and Z. Hao, *ibid.* **44**, 2732 (1991); G. Blatter, M. V. Fiegel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur (unpublished); K. H. Fischer, Physica C **178**, 161 (1991); S. Ryu, S. Doniach, G. Deutscher, and A. Kapitulnik, Phys. Rev. Lett. **68**, 710 (1992).

[2] P. H. Kes, J. Aarts, V. M. Vinokur, and C. J. van der Beek, Phys. Rev. Lett. **64**, 1063 (1990); H. Raffy, S. Labdi, O. Laborde, and P. Monceau, *ibid.* **66**, 2515 (1991); T. Fukami, K. Miyishi, T. Nishizaki, Y. Horie, F. Ichikawa, and T. Aomine, Physica C **202**, 167 (1992).

[3] G. Blatter, V. B. Geshkenbein, and A. I. Larkin, Phys. Rev. Lett. **68**, 875 (1992); Y. Iye, I. Oguro, T. Tamegai, W. R. Datars, N. Motohira, and K. Kitazawa, Physica C **199**, 154 (1992).

[4] V. Hardy, D. Groult, J. Provost, M. Hervieu, B. Raveau, and

S. Bouffard, Physica C **178**, 255 (1991).

[5]L. Civale, A. D. Marwick, T. K. Worthington, M. A. Kirk, J. R. Thompson, L. Krusin-Elbaum, Y. Sun, J. R. Clem, and F. Holtzbelg, Phys. Rev. Lett. **67**, 648 (1991).

[6]L. Klein, E. R. Yacoby, Y. Wolfus, Y. Yeshurun, L. Burlachkov, B. Ya Shapiro, M. Konczykowski, and F. Holtzberg, Phys. Rev. B **47**, 12 349 (1993).

[7]W. Gerhauser, G. Ries, H. W. Neumuller, W. Schmidt, O. Eibl, G. Saemann-Ischenko, and S. Klaumunzer, Phys. Rev. Lett. **68**, 879 (1992).

[8]J. R. Thompson, Y. R. Sun, H. R. Kerchner, D. K. Christen, B. C. Sales, B. C. Chakoumakos, A. D. Marwick, L. Civale, and J. O. Thompson, Appl. Phys. Lett. **60**, 2306 (1992).

[9]T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, R. B. van Dover, and J. V. Waszczak, Phys. Rev. B **38**, 5102 (1988); J. H. Cho, Zhidong Hao, and D. C. Johnston, *ibid.* **46**, 8679 (1992); J. C. Martinez, S. H. Brongersma, A. Koshelev, B. Ivlev, P. H. Kes, R. P. Griessen, D. G. de Groot, Z. Tarnavski, and A. A. Menovsky, Phys. Rev. Lett. **69**, 2276 (1992).

[10]D. R. Nelson and V. M. Vinokur, Phys. Rev. Lett. **68**, 2398 (1992).

[11]N. Motohira, K. Kuwahara, T. Hasegawa, K. Kishio, and K. Kitazawa, J. Ceram. Soc. Jpn. Int. Ed. **97**, 994 (1989).

[12]A. M. Campbell and J. E. Evetts, Adv. Phys. **21**, 199 (1972).

[13]F. Hellman, E. M. Gyorgy, and R. C. Dynes [Phys. Rev. Lett. **68**, 867 (1992)] have recently reported that in samples with highly anisotropic shape, such as our crystals, the critical currents in the bulk are forced to flow perpendicular to the short direction. Thus, regardless of any intrinsic anisotropy, the irreversible magnetization points along the shortest length, i.e., the *c* axis.

[14]M. J. Naughton, R. C. Yu, P. K. Davies, J. E. Fischer, R. V. Chamberlin, Z. Z. Wang, T. W. Jing, N. P. Ong, and P. M. Chaikin, Phys. Rev. B **38**, 9280 (1988).

[15]N. Chikumoto, M. Konczykowski, N. Motohira, and K. Kishio, Physica C **199**, 32 (1992); Y. Heshurun *et al.*, Cryogenics **29** (Suppl.), 258 (1989).

[16]V. N. Kopylov, A. E. Koshelev, I. F. Schegolev, and T. G. Togonidze, Physica C **170**, 291 (1990).