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Local Electrodynamics in Heavy Ion Irradiated Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Transport measurements in the flux transformer and $c$-axis geometries are used to investigate vortex dynamics in heavy ion irradiated BSCCO crystals. In the flux transformer geometry there is a range of fields, temperatures, and angles where the primary and secondary voltages show close correspondence, as observed in YBCO. This occurs because the columnar defects suppress thermal fluctuations and decrease $\rho_c$. Values for $\rho_{ab}$ and $\rho_c$ are extracted from the flux transformer data assuming local anisotropic electrodynamics and compared with directly measured $c$-axis data. Good agreement confirms the validity of local resistivity. This is supported by both measurement configurations indicating that $\rho_c$ vanishes faster than $\rho_{ab}$. [S0031-9007(96)00874-5]

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Measurements in the flux transformer (FT) geometry are a useful means of probing the dimensionality or longitudinal correlation of vortices in the liquid state in both Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) [1–3] and YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) [4–8]. However, the difficulties associated with interpretation of data measured in the quasiforce free configurations have been discussed in detail by Brandt [9]. Reported FT data indicate that the entire vortex liquid state in BSCCO is 2D [1–3] since flux cutting always generates a sizable voltage drop along the $c$ axis in the linear resistivity regime. Thus the primary voltage $V_p$ is always much larger than the secondary voltage $V_s$. On the other hand, the resistive transition in the FT geometry in (twinned) YBCO [10] apparently proceeds via two steps. $V_p$ and $V_s$ appear at almost the same temperature and show close correspondence over a small range of temperatures. This implies that $\rho_{ab}$ is measurable before $\rho_c$ and is claimed to result in a “disentangled” or 3D vortex liquid. At some higher thickness dependent temperature, longitudinal correlation is also lost and $\rho_c$ becomes measurable at the onset of an “entangled liquid.” Entanglement should, however, not be confused with flux cutting which is what causes the $c$-axis dissipation and results in a difference between $V_p$ and $V_s$. Subsequently, it has been shown [11] that close correlation of the voltages in the FT geometry in YBCO only occurs in the presence of twin boundaries, a type of correlated disorder. In clean YBCO crystals, correlation is lost in all directions simultaneously at what is suggested to be a first order phase transition [12]. Recent measurements on BSCCO also suggest that the melting transition [13,14] involves a loss of $c$-axis correlation [15].

Despite the large anisotropy of BSCCO there are indications that vortices in heavy ion irradiated (HII) BSCCO behave as lines rather than independent stacks of pancakes [16,17]. This is associated with the topological correspondence between the columnar defects induced by the HII and the stacks of pancake vortices. Static magnetization measurements (of the vortex solid) show uniaxial enhancement of the irreversibility line when the magnetic field is applied parallel to the columnar defects [16,18]. Seow et al. [17] have found similar enhancement in HII BSCCO using transport measurements (which probe the liquid state).

Possible nonlocal effects in the electrodynamic behavior of the vortex liquid should be directly related to the vortex dimensionality. The finite line tension of a vortex can, under certain conditions, induce a voltage distantly from the position where (nonuniform) currents act on it: precisely the situation which is probed by the FT geometry. Safar et al. [4] found evidence for nonlocal behavior in twinned YBCO crystals using this method. Their conclusions are based on differences between the apparent ratios $\rho_{ab}/\rho_c(T)$ determined from FT and direct $c$-axis configurations. The effect was explained using a phenomenological hydrodynamic theory of a viscous vortex liquid by Huse and Majumdar [19]. Eltsev and Rapp, on the other hand [6,8], using similar crystals and parameters to Safar et al. [4], satisfactorily explained their data using local theory. Measurements on BSCCO by Busch et al. [1] also showed that their data were described well by local electrodynamics. This is less surprising since, in as-produced BSCCO, the stacks of pancake vortices have a vanishingly small line tension. The recent data suggesting a finite line tension is apparent for vortices in HII BSCCO [16–18] are supported by theoretical considerations which indicate that such defects increase the $c$-axis correlation by suppressing thermal fluctuations of pancake vortices [20]. This suggests that nonlocal effects similar to those apparently observed in the more 3D YBCO system [4] might be observed in HII BSCCO, and this is the subject of this paper.
Samples of BSCCO were grown in an infrared furnace [21]. Both surfaces of the selected crystals were optically smooth. Four 25 μm gold wires were attached to each (ab-plane) surface in the FT geometry. Contact resistances are less than 4 Ω for each pair. The configuration is shown in the inset in Fig. 1. Two crystals were measured. Crystal K1 has dimensions of 1.04 × 0.41 × 0.01 mm while crystal K2 has dimensions of 1.03 × 0.52 × 0.01 mm. The electrode spacing is Δ1 = 0.25 mm. Reliability of the FT data is carefully screened by checking the symmetry when current is injected from each side of the crystal. Measurements were made using a lock-in amplifier and low noise transformer at a frequency of 72.8 Hz and current of 2 mA. This current is well within the linear regime for all temperatures. This was verified by measuring all configurations at currents between 0.1 and 10 mA as well as making dc IV measurements. Nonlinear effects appear above 6 mA, where heating effects cannot be precluded. The crystals were irradiated at GSI Darmstadt, with a 2.25 GeV Au ion beam aligned close to the c axes. We define matching fields, BΦ, where the vortex spacing δ0 = (Φ0/B)1/2 is equal to the average defect spacing d. Crystal K1 was irradiated to BΦ = 0.5 T and K2 to BΦ = 2.0 T. Transmission electron microscopy studies show that the irradiation induces continuous columnar defects with radius b0 = 3.5 nm.

We begin with the qualitative features of FT data for irradiated BSCCO. Figure 1 presents Vp = V23(I14) and Vs = V02(I14) for crystal K1. Remarkable reentrant behavior is exhibited by Vs at all fields shown below and slightly above the matching field. Vp and Vs show close correspondence in a region above where they vanish for fields below BΦ. The amplitude of the peak in Vp grows with field, shows a maximum between 60 and 70 K, and disappears above 1.3 T for crystal K1 (BΦ = 0.5 T) and above 3 T for K2 (BΦ = 2.0 T). No such peaks in Vs were observed before irradiation. Much smaller peaks of a qualitatively different nature become apparent in Vs at high currents (=10 mA) before irradiation, as reported elsewhere [1,3]. These latter peaks, which are dependent on the current amplitude [3], disappear below the sensitivity at temperatures well above Vp. The peaks seen in Fig. 1 closely resemble those observed in deoxygenated [22] twinned YBCO crystals and are associated with the correlated disorder. For B > BΦ, interstitial vortices dominate the behavior similar to as-produced BSCCO. Interaction between the vortices in different layers becomes weaker than intralayer interactions so that the reentrant Vp disappears.

Figure 2 presents a phase diagram constructed from the FT data in Fig. 1. It indicates Tn(B), where Vp disappears below the resolution. This line crosses (BΦ = 0.5 T) close to T* = 69 K, where vortex localization on the columnar defects is expected in BSCCO [20]. There is a rapid drop in the pinning ability of the defects at a temperature, Tl, where the thermal energy becomes comparable to the pinning energy. This occurs for sample K1 just below 80 K in agreement with other data [18]. The inset of Fig. 2 shows the angular dependence of Vp and Vs at 72.8 K for crystal K1 at 0.5 T as the magnetic field is rotated through alignment with the columnar defects. The peak in Vs extends to 60° to 70° from the c axis, consistent with other reports [23,24]. The dip near θ = 0 is the direction of the irradiation. There is also a small angular range where Vp and Vs show correspondence. From the results of Fig. 1, we calculate the value of ρc assuming local electrodynamics. We use the anisotropic approximation based on the Laplace equation following Busch et al. [1] and calculate (ρc/ρab)1/2 = (L/πτ)arccosh(Vp/Vs) and (ρc/ρab)1/2 = Vp/L/π(Δs), where Δs is the electrode spacing and w the crystal width. The resistivity components can then be separated. By injecting current along the c axis, ρc can also be obtained from Vs = V23(I14) and ρc = VcLw/I, where I is the current, L the length, w the crystal width, and t the thickness. This “direct” measurement assumes uniform current flow along the c axis and is usually justified over a large range of temperatures because of the extreme resistive anisotropy (γ2 = ρc/ρab = 1702) which means

![FIG. 1. Primary, V23(I14) (solid line), and secondary, V02(I14) (points), voltages for crystal K1 for B//c//defects of 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, and 1.3 T. BΦ = 0.5 T. The inset shows the contact configuration.](image1)

![FIG. 2. The field dependence of the Tn(B), where Vp vanishes for crystal K1. The line is a guide, and the temperatures T* and Tl are discussed in the text. The inset shows Vp(θ) and Vs(θ) at 72.8 K and 0.5 T. θ = 0 corresponds to B//defects.](image2)
the crystal is effectively “stretched” along the c axis by a factor of 170. This results in an “isotropic” c-axis dimension of about 2 mm, as compared to the electrode spacing which is 10 times smaller. The values of \( \rho_c(T) \) from both methods are presented for different fields in an Arrhenius plot in Fig. 3. Very satisfactory agreement is apparent. We have also used \( V_p \), together with the directly measured \( \rho_c \), to recalculate \( V_s \) to see whether this would correctly reproduce the remarkable reentrant peak. This result is shown for crystal K1 in Fig. 4 at 1.0 T for \( B//c \), also yielding satisfactory agreement. Figure 5 shows the angular dependence of the extracted resistivity components from the data in the inset of Fig. 2. Both \( \rho_c \) and \( \rho_{ab} \) show a cusp for \( B//\) defects.

In unirradiated BSCCO crystals, the anisotropy is sufficiently large at all temperatures that \( V_s \) shows a weak peak [1] or does not reappear at all before \( V_p \) disappears below the sensitivity [2]. This means there is a large voltage drop along the c axis wherever the primary voltage is measurable. Whenever there is a current component parallel to the field, as there is in all these measurements, flux cutting of some kind must occur to produce a voltage component along the direction of the field [9].

This is well known in conventional superconductors, where the flux structure in the force free configuration can be extremely complex and the \( J_c \) nonlocal [25]. In 2D systems with weak pinning, flux cutting is very easy [26]. Then the external field can be regarded separately from the flux rings produced by the self-field of the (c-axis component of the) current. The system is linear, and local anisotropy theory can be used [1]. On the other hand, in irradiated crystals, strong pinning is introduced and \( \rho_c \) is dramatically reduced in the mixed state for \( B//\) defects [17]. We understand the data as follows. In an applied field, \( \rho_{ab}(T) \) decreases monotonically with temperature. However, \( \rho_c \) displays a pronounced maximum so that the anisotropy, \( \gamma^2 = \rho_c/\rho_{ab} \) also shows a maximum. In the FT geometry, the current is injected into one face only and penetrates the crystal to a distance \( z_{eff} = L \pi^{-1}(\rho_{ab}/\rho_c)^{1/2} \), where \( L \) is the length of the crystal [1]. Clearly the maximum in \( \rho_c \) corresponds to a minimum in \( z_{eff} \). The value we estimate is about 1 \( \mu \)m, considerably smaller than the crystal thickness. Since \( V_s \) is sensitively determined by the proximity of the current to the bottom electrodes, it results in \( V_s \) dropping below the noise level close to but below \( T_c \). At lower temperatures, \( \rho_c \) falls much faster than \( \rho_{ab} \) in HII BSCCO, reducing the effective anisotropy. Thus \( z_{eff} \) is increased, and \( V_s \) reappears in the vortex liquid state as shown in Fig. 1. What is more important is that \( V_s \) approaches and shows close correspondence with \( V_p \) in a small window of temperatures before both disappear, as also seen in the much more 3D YBCO system [4–7]. This implies \( \rho_c \) has dropped to a very small value, an effect which indicates a strong enhancement in the correlation of vortices in the vortex liquid. The columnar defects effectively increase the interlayer coupling by suppressing thermal fluctuations of pancake positions. Our observations are also in agreement with previous studies showing that even weak random pinning strongly suppresses the helical instabilities which result in flux cutting in the force free configuration [9].

Next we consider the validity of local electrodynamics to the behavior of the samples studied. There is a clear qualitative resemblance of the data in Fig. 1 to that in twinned YBCO where nonlocal effects were inferred [4]. There are two ways in which nonlocality can be established. One is to show a thickness dependence in \( \rho_c \) itself. The other way is to show that local theory does not work. However, the results in Fig. 3 suggest that \( \rho_c \) is accurately recalculated by local theory. The curves are all smooth functions, suggesting a uniform resistive mechanism at all temperatures. A stronger test of locality is consistency between the apparent ratios of \( \rho_c/\rho_{ab} \) extracted from local theory from the two geometries where the current is injected parallel and perpendicular to the \( ab \) planes [4]. The inset in Fig. 3 shows the temperature dependence of the ratios, \( V_{67}/V_{23}(I_{14}) \) and \( V_{36}/V_{27}(I_{18}) \), for crystal K1 at 0.5 T.

![FIG. 3. Directly measured \( \rho_c \) extracted from \( V_{27}(I_{18}) \) (solid lines) and from the FT data (points) as discussed in the text for the same fields as in Fig. 1.](image1)

![FIG. 4. Primary \( V_p(T)/I \) and secondary \( V_s(T)/I \) apparent resistances (points), and calculated secondary apparent resistance from the primary and c-axis voltages (solid line) for crystal K1 at 1.0 T. The inset shows the temperature dependence of the ratios \( V_{67}/V_{23} \) and \( V_{36}/V_{26} \) at 0.5 T for crystal K1.](image2)
When current is injected in the top face and \( \rho_c \) drops more rapidly than \( \rho_{ab} \), \( V_{67}/V_{23}(14) \) should approach unity, as it indeed does. Accordingly, \( V_{36}/V_{27}(18) \) should approach zero in a local scenario since the current shrinks away from the voltage electrodes before \( \rho_{ab} \) vanishes. In both crystals, \( V_{36} \) disappears before \( V_{27} \), resulting in a ratio which approaches zero. These data imply the validity of local electrodynamics in irradiated BSCCO crystals. We cannot entirely preclude the possibility that nonlocal effects might affect \( \rho_c \) in the same way for both geometries, thereby allowing the local theory to be used. However, the consistency of the data makes this seem unlikely. Therefore we suggest that the close correspondence between \( V_p \) and \( V_z \) arises not because of nonlocal effects but because \( \rho_c \) becomes small (in a narrow range of angles for \( B/\parallel \text{defects} \)) and \( z_{\text{eff}} \) approaches the crystal thickness, resulting in an almost uniform Lorentz force. Similar current redistribution effects were invoked [27] to explain a simultaneous peak in \( V_z \) and minimum in \( \rho_c \) for \( B/\parallel ab \) planes in BSCCO crystals.

Finally, the evidence supporting an enhanced \( c \)-axis correlation is briefly discussed. The angular dependence of the extracted resistivities shown in Fig. 5 shows that both components are reduced for \( B/\parallel \text{defects} \), as expected for strong uniaxial pinning and a finite line tension. Well away from alignment, the (scaled) resistivity reverts to the strong uniaxial pinning and a finite line tension. Well away from alignment, the (scaled) resistivity reverts to the finite line tension. Well away from alignment, the (scaled) resistivity reverts to the finite line tension.

In conclusion, we have shown that correlated disorder in the form of columnar defects modifies the effective anisotropy in the vortex liquid state in BSCCO. This results from strong uniaxial liquid state apparent for fields parallel to the defects. Our data are consistent with an anisotropic local resistivity even though there is a clear increase in the \( c \)-axis correlation due to the defects.

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[22] D. Lopez et al. (to be published).