Structure of Vortex Liquid Phase in Irradiated $Bi_2Sr_2CaCu_2O_{8-\delta}$ Crystals

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(Received 10 September 1998)

The c-axis resistivity in irradiated and in pristine $Bi_2Sr_2CaCu_2O_{8-\delta}$ crystals is measured as a function of the in-plane magnetic field component at fixed out-of-plane component $B_\perp$ in the vortex liquid phase at $T = 67$ K. From this data we extract the dependence of the phase difference correlation length inside layers on $B_\perp$ and estimate the average length of the vortex line segments confined inside columnar defects as a function of the filling factor $f = B_\perp/B_\Phi$. The maximum length, about 15 interlayer distances, is reached near $f \approx 0.35$. [S0031-9007(98)08327-6]

PACS numbers: 74.60.Ge, 74.25.Fy, 74.62.Dh

The structure of the vortex liquid in highly anisotropic layered superconductors with columnar defects (CDs) produced by heavy ion irradiation is one of the most intriguing questions in the current study of the vortex state in high temperature superconductors. For the most anisotropic $Bi_2Sr_2CaCu_2O_{8-\delta}$ (Bi-2212) superconductor without strong disorder, neutron scattering and Josephson plasma resonance (JPR) data provide evidence in favor of a pancake liquid with very weak correlations of pancakes in different layers [1–3]. When CDs are introduced into these crystals a large decrease in the reversible magnetization is observed [4], indicating that pancakes are predominantly situated on the CDs, even in the liquid state. Recent studies of JPR [5,6] and c-axis transport [7,8] in irradiated Bi-2212 crystals reveal enhancement of c-axis correlations in some interval of out-of-plane magnetic fields, $B_\perp$, below the matching field, B_Φ, at temperatures $T \sim 70$ K. In other words, pancakes at these fields and temperatures appear to form aligned segments of vortex lines inside CDs, while outside of this region they are better described as a liquid of weakly c-axis-correlated pancakes, as in pristine crystals. Both c-axis transport and JPR involve the flow of Josephson currents and are thus sensitive to the misalignment of pancake vortices between adjacent planes. CDs aligned with the c axis will promote interplane pancake alignment in a region of temperature where pancakes remain largely localized on CDs. Even in the liquid state, where pancakes are mobile, filling of the available CD sites should lead to enhanced c-axis correlation from statistical considerations alone. In previous c-axis transport measurements [7], a dip in the magnetoresistance, $\rho(B_\perp)$, of a Bi-2212 crystal was observed at a magnetic field corresponding to a filling factor of CDs, $f = B_\perp/B_\Phi \approx 1/3$.

So far there has been no technique available for providing quantitative information on the degree of c-axis correlation or on the length of pancake line segments. In addition, it is unclear whether vortex interactions play a significant role in enhancing correlation in the liquid state. Previously, a method was proposed, but not yet realized, to extract the pancake density correlation function using data for JPR frequency as a function of $B_\parallel$ at fixed $B_\perp$ [9]. In this Letter we determine the average length of vortex line segments as a function of $B_\perp$, i.e., of the filling factor f, from transport measurements on single crystals of Bi-2212 with and without CDs. For this we have developed a method for extracting the phase difference correlation function along the layer from measurements of the c-axis conductivity, σ_c, as a function of the magnetic field component parallel to the layers, $B_\parallel$, at fixed $B_\perp$. The component $B_\perp$ establishes the vortex state to be studied, while the component $B_\parallel$ serves as a probe of this state, as described below. Knowing the phase difference correlation length, we estimate the pancake density correlation length along the c axis.

In Josephson coupled superconductors in the presence of a c-axis current, voltage is induced by slips of the phase difference between layers, $\varphi_{n,n+1}(\mathbf{r}, t)$, as described by the Josephson relation $V_{n,n+1} = (\hbar/2e)\dot{\varphi}_{n,n+1}$. Here n labels layers, $\mathbf{r} = x, y$ are coordinates in the ab plane, and t denotes the time. The c-axis conductivity in the vortex liquid state is determined by the Kubo formula [3]

$$\sigma_c(B_\perp, B_\parallel) = (s J_0^2/2T) \int_0^\infty dt \int d\mathbf{r} G(\mathbf{r}, t), \quad (1)$$

$$G(\mathbf{r}, t) = 2\langle \sin \varphi_{n,n+1}(0,0) \sin \varphi_{n,n+1}(\mathbf{r}, t)\rangle \approx \langle \cos[\varphi_{n,n+1}(\mathbf{r}, t) - \varphi_{n,n+1}(0,0)]\rangle, \quad (2)$$

where J_0 is the Josephson critical current and s is the interlayer distance. Time variations of the phase difference are caused by mobile pancakes [10] induced by $B_\perp$ and by mobile Josephson vortices induced by the parallel component $B_\parallel$. In the lowest order in Josephson coupling we split $[\varphi_{n,n+1}(0,0) - \varphi_{n,n+1}(\mathbf{r}, t)]$ into the contribution induced by pancakes and that caused by the unscreened parallel component $B_\parallel$. Assuming that $B_\parallel$ is along the x axis, we obtain a simple expression for the contribution of the parallel component to the phase difference,

$$\varphi_{n,n+1}(0,0) - \varphi_{n,n+1}(\mathbf{r}, t) \approx [\varphi_{n,n+1}(0,0) - \varphi_{n,n+1}(\mathbf{r}, t)]_{B_\parallel=0} - 2\pi s B_\parallel y/\Phi_0. \quad (3)$$

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Inserting this expression into Eqs. (1) and (2) we obtain

$$\sigma_c(B_\perp, B_\parallel) = (\pi s J_0^2/T) \int dr r \tilde{G}(r, B_\perp) J_0(\alpha B_\parallel r), \tag{4}$$

where $J_0(x)$ is the Bessel function, $\alpha = 2\pi s/\Phi_0$, and

$$\tilde{G}(\mathbf{r}, B_\perp) = \int_0^\infty dt G(\mathbf{r}, t, B_\perp). \tag{5}$$

The function $G(\mathbf{r}, t)$ describes the dynamics of the phase difference caused by mobile pancakes. If $g(B_\perp, B_\parallel) = \sigma_c(B_\perp, B_\parallel)/\sigma_c(B_\perp, 0)$ is known in the vortex liquid, the correlation function $G(r) = \tilde{G}(r) J_0^2 \Phi_0^2/4\pi s T \sigma_c(B_\perp, 0)$ may be found using the inverse Fourier-Bessel transform,

$$G(r, B_\perp) = \int dB_\parallel B_\parallel g(B_\parallel, B_\perp) J_0(\alpha B_\parallel r). \tag{6}$$

The correlation lengths R and R_1 of this function are defined by the relations

$$R^2 = \int_0^\infty dr \frac{rG(r)}{G(0)}, \quad R_1^2 = \int_0^\infty dr \frac{r^3 G(r)}{R^2 G(0)}. \tag{7}$$

Note that R_1 is related to the coefficient of the $B_\parallel^2$ term in the expansion of $g(B_\perp, B_\parallel)$ in $B_\parallel^2$,

$$g(B_\perp, B_\parallel) \approx 1 - [\pi s R_1(B_\perp)/\Phi_0]^2 B_\parallel^2. \tag{8}$$

Thus $R_1(B_\perp)$ can be obtained independently from data for $\sigma_c(B_\perp, B_\parallel)$ at small $B_\parallel$.

Such a procedure to obtain the function $G(r, B_\perp)$ is valid if the vortex state depends weakly on the Josephson coupling and hence on the probe field $B_\parallel$ (which affects Josephson coupling). Then this method is nondestructive. Let us check first under what conditions we can neglect the effect of Josephson coupling on the equilibrium vortex state. The energy of Josephson coupling in the correlated area πR^2 is $\pi E_0 R^2/\lambda_J^2$, which should be much smaller than the temperature T to be treated as a perturbation [9]. Here $E_0(T) = \Phi_0^2 s/16\pi^3 \lambda_{ab}^2(T)$. For Bi-2212, with $\gamma \approx 300$ and $\lambda_{ab}(0) \approx 2000$ Å, the Josephson coupling in the correlated area is $\approx 0.2T$ at the maximum value of R found below and at $T > 60$ K. Thus the effect of Josephson coupling, and hence $B_\parallel$, on the equilibrium vortex state may be neglected. For dynamical parameters, such as σ_c, higher order terms in Josephson coupling describing dynamic screening of $B_\parallel$ omitted in Eq. (3), may be important. This will be discussed below.

We anticipate that in the pancake vortex liquid state in pristine crystals the characteristic lengths R and R_1 of the correlation function $G(r)$ are of order of the intervortex distance, $a = (\Phi_0/B_\perp)^{1/2}$, because each pancake here is mobile and induces phase slippage as described in Ref. [10]. In irradiated crystals with CDs we anticipate much bigger R and R_1 if pancakes form long segments of lines inside CDs. Then only ends of segments contribute significantly to the phase difference $\varphi_{n,n+1}(\mathbf{r}, t)$ and lead to suppression of Josephson coupling and σ_c, while the effect of pancakes in neighboring layers inside the segments is much smaller.

For our experiments, high quality Bi-2212 crystals ($T_c \simeq 85$ K) of about $1 \times 1.5 \times 0.02$ mm^3 were used. The irradiation by 1.2 GeV U^{238} ions was performed on the ATLAS accelerator (ANL). According to TRIM calculations these ions produce in Bi-2212 continuous amorphous tracks with diameter 4–8 nm and length 25–30 μm. Below, we present the results for the samples irradiated with a density of CDs corresponding to the matching field $B_\Phi = 2$ T and for a reference pristine sample.

Our measurements of c-axis conductivity were carried out in a cryostat with *two* superconducting magnets providing magnetic fields in orthogonal directions. The magnets are controlled independently and provide fields up to 8 T in one direction and up to 1.5 T in the other direction. Samples can be oriented along the axis of either magnet. Misalignment of the crystal c axis with respect to the perpendicular component $B_\perp$ was detected by the asymmetry of $\rho_c(B_\parallel)$ with respect to the sign of $B_\parallel$. We adjusted the direction of the field components, providing asymmetry below 5% at $B_\parallel > 2$ T and below 10% at lower fields. The normalized conductivity $g(B_\parallel)$ was calculated using the average resistivity $\overline{\rho}_c(B_\parallel) = [\rho_c(B_\parallel) + \rho_c(-B_\parallel)]/2$. Two silver contact pads were deposited on both sides of the sample using a mechanical shadow mask. The mask provided a clean surface rim $\sim$0.1 mm from the sample edges and 25 μm separation between current and potential pads. The area of the contact was $\approx$0.75 mm^2 for current and $\approx$0.05 mm^2 for potential terminals. The resistance of the current pads at room temperature was $\approx 2\ \Omega$. A current of 1 mA, driven through the sample, provides an Ohmic I-V regime. For very anisotropic Bi-2212, in our range of the magnetic field and temperatures, in-plane conductivity, $\sigma_{ab} \sim 10^3 \sigma_c$ [11], providing nearly equipotential current distribution in the ab plane, at least in the central area of the sample. Thus the contribution of σ_{ab} to the anisotropic conductivity is weak and can be neglected, in the limit of small pad separation. Thus a standard 4-probe method can be used for ρ_c measurement instead of the complicated multiterminal Montgomery analysis. The temperature was stabilized with an accuracy ± 50 mK. The resistivity $\rho_c(B_\parallel)$ was measured in the $B_\perp$ interval where g at maximum $B_\parallel$ drops with $B_\parallel$ at least to the value 0.2.

In Fig. 1 we present ρ_c as a function of $B_\parallel^2$ at different $B_\perp$ for (a) irradiated and (b) pristine crystals. For irradiated crystals at low $B_\parallel$ the resistance increases quadratically with $B_\parallel$ as prescribed in Eq. (8). In contrast, for the pristine crystal we observed that ρ_c increases quadratically at high $B_\parallel$, but exhibits a minimum at low fields that is not described by Eq. (8). This low field behavior is caused by dynamic screening of $B_\parallel$ that results in additional dissipation at low fields, due to the combined effects of motion of Josephson vortices induced by $B_\parallel$ and of pancake vortices. These effects are not important at

high fields. They do not appear in the irradiated crystal due to pinning of the Josephson vortices.

In Fig. 2 we show the dependence $g = \sigma_c(b)/\sigma_c(0)$ on $b = B_\parallel/(B_s B_\perp)^{1/2}$ for irradiated and pristine samples at different $B_\perp$. Here $B_s = \Phi_0/2\pi s^2$. For the pristine crystal the values $\sigma_c(B_\perp)$ at $B_\parallel = 0$ were determined by extrapolation of $\rho_c(B_\parallel)$ from the high field quadratic dependence to zero as shown in Fig. 1b by the dashed lines. Note that for the pristine crystal all three curves coincide at high fields, demonstrating scaling of the correlation length R with a. Such a scaling is not observed for the irradiated crystal at $B_\perp \leq 1.2$ T, because the average distance between CDs, $a_\Phi = (\Phi_0/B_\Phi)^{1/2}$, gives another length scale in addition to a. More importantly, we see that g drops with $B_\parallel$ much faster for the irradiated sample. The correlation length $R(B_\perp)$ is related via $R \approx \Phi_0/\tilde{B}_\parallel s$ to the magnetic field $\tilde{B}_\parallel$ which characterizes the scale of the drop of σ_c with $B_\parallel$. Here $\tilde{B}_\parallel$ is the magnetic field at which flux in the area Rs is $\approx\Phi_0$. If we define the characteristic field $\tilde{B}_\parallel$, as given by $g(\tilde{B}_\parallel) = 0.1$, then from Fig. 2 at $B_\perp = 0.2$ T, we estimate for the pristine crystal $R/a \approx 2.5$, while for irradiated one $R/a \approx 8$. As one can see from Fig. 2, at the high fields $B_\parallel$ used in our measurements, the dependence $g(B_\parallel)$ is close to exponential, and we use this to extrapolate $g(B_\parallel)$ to higher fields. Then we determine $G(r)$ in the interval $r < r_m \approx 0.5$ μm by use of Eq. (6). Accuracy of our experimental data and of the inverse Fourier-Bessel transformation is not sufficient to obtain $G(r)$ at $r > r_m$.

In Fig. 3a we show the functions $G(r/a)$ and in Fig. 3b the same data versus $x = r/R$, where the scaling length $R(B_\perp, B_\Phi)$ is defined by Eq. (7). For the pristine crystal at $B_\perp = 0.1$ and 0.2 T we obtain $R(B_\perp) \approx a$. The curve for $B_\perp = 0.2$ T is plotted by the dashed line, and it practically coincides with that at $B_\perp = 0.1$ T. For the irradiated sample we show the curves corresponding to regions below, above, and at the position of the dip in the magnetoresistance curve, $\rho_c(B_\perp, 0)$ from Ref. [7] as shown in the inset. It is evident in Fig. 3a that the rate of decay of correlations with distance is not a monotonic function of $B_\perp$ and is a minimum at a value corresponding to the dip in $\rho_c(B_\perp)$. Notably all these curves quite accurately merge in Fig. 3b, providing *a universal function* $G(x)$ for both pristine and irradiated samples with a single scaling length R, although the irradiated sample is characterized generally by two lengths a and a_Φ. In comparison with pristine crystals CDs simply diminish the effective concentration of pancakes acting on Josephson coupling by the factor a^2/R^2.

The correlation length R as a function of $B_\perp$ is shown in Fig. 4. It exhibits a distinct maximum, $R/a \approx 4$, at $f \approx 0.35$, again coinciding with the position of the dip in $\rho_c(B_\perp)$. At $f = 0.35$ the ratio of $R(B_\perp)$ for irradiated and pristine crystals is about 4 times.

The length R_1 obtained from the function $G(r)$ using Eq. (7) is $\approx 2R$ at all values $B_\perp$ studied. The same length determined directly from the function $g(B_\parallel)$ at small $B_\parallel$ using Eq. (8) is $\approx 3R$. Thus we estimate the accuracy of extracting $G(r)$ as $\approx$30%.

In order to determine the c-axis correlations of pancakes and to explain scaling, we note that at small f pancakes are positioned mainly inside CDs and hence the drop in the phase difference correlations is caused by interruptions in pancake arrangement inside CDs. Namely, we suppose that the phase difference $\varphi_{n,n+1}(\mathbf{r})$ is induced when a columnar defect in the layer n is occupied by a pancake, but the site inside the same CD in the layer $n + 1$ is empty (and vice versa). At larger f the unpinned pancakes also contribute to the decay of correlations. Scaling for both pristine and irradiated crystals means that ends of vortex segments inside CDs act on the phase difference correlations as unpinned pancakes. The net concentration of interruptions and unpinned pancakes is $1/R^2$, i.e., the average length of vortex segments is $L/s \approx R^2/a^2$. In the most aligned vortex liquid, at $f \approx 0.35$, we estimate $L/s \approx 15$. This is much larger than $L_0/s \approx 1/(1 - f) \approx 1.5$

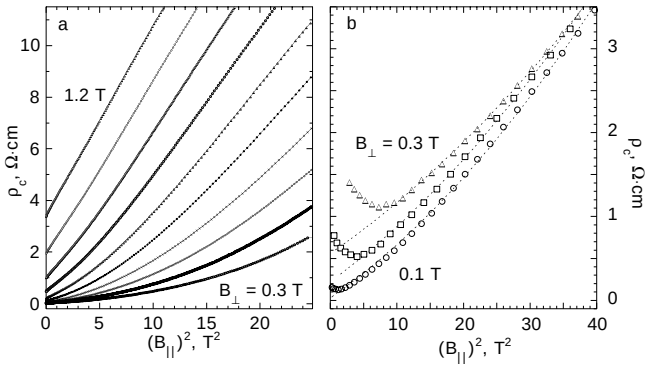

FIG. 1. Dependence of resistivity ρ_c versus $B_\parallel^2$ for perpendicular components $B_\perp$, increasing sequentially with the step 0.1 T in irradiated (a) and pristine (b) crystals.

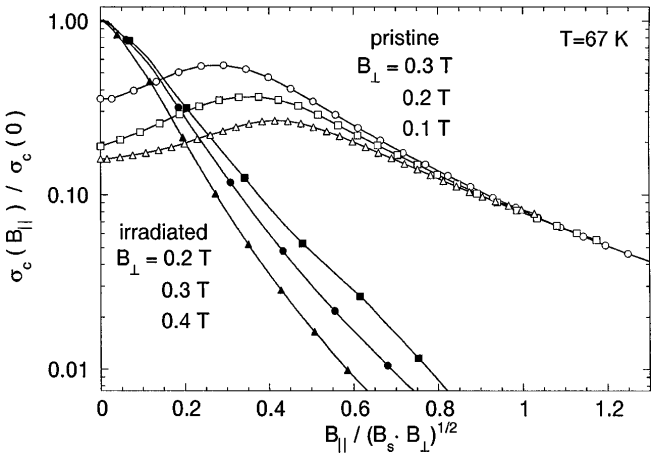

FIG. 2. Dependence $g(B_\parallel) = \sigma_c[B_\parallel/(B_s B_\perp)^{1/2}]/\sigma_c(0)$ in irradiated and pristine crystals.

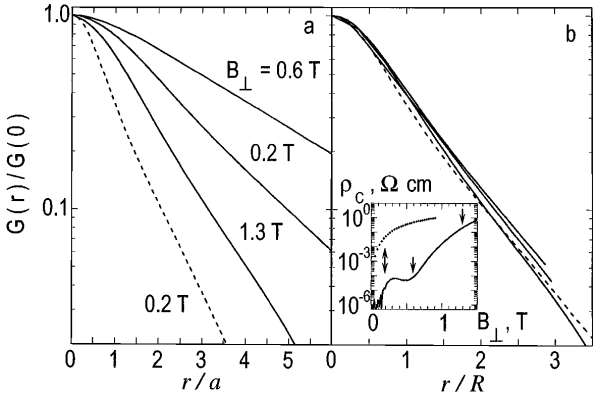

FIG. 3. The functions $G(r/a)$ (a), and $G(r/R)$ (b) as extracted from $g(B_\parallel)$ for irradiated (solid) and for pristine (dashed) samples. Inset: $\rho_c(B_c)$ at $B_\parallel = 0$ from Ref. [7]. Arrows indicate $B_\perp$ values for the presented $G(r)$ curves.

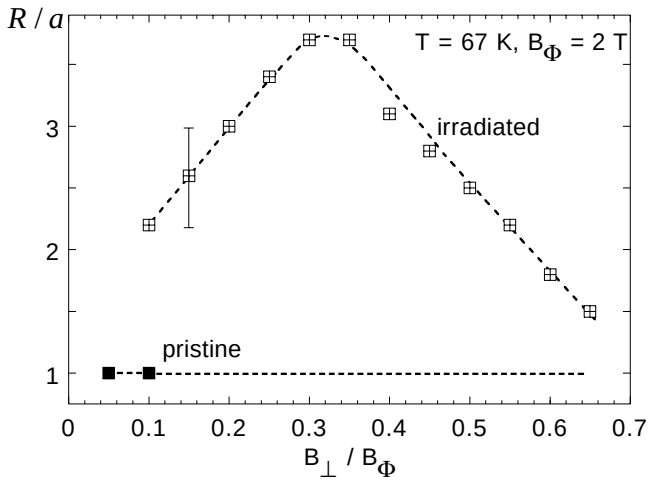

FIG. 4. Dependence of the correlation length R as a function of filling factor, $f = B_\perp/B_\phi$, of columnar defects for irradiated and pristine samples. Dashed lines are guides.

in the model of noninteracting pancakes positioned randomly on CDs. Thus we conclude that interaction of pancakes is important for enhanced alignment inside CDs.

In the hierarchy of interactions in the presence of CDs, both the pinning energy per pancake and the intralayer repulsion energy of pancakes are characterized by the same energy scale E_0. The scale of magnetic pair attraction of pancakes in different layers is smaller by the factor s/λ_{ab}. The random distribution of CDs is important. Repulsion between vortices in the same layer leads to a significant increase of pancake energy inside CDs situated near those already occupied by pancakes [12]. As $B_\perp$ increases, some CDs become more favorable for filling by pancakes, while others remain unoccupied. Another important point is that favorable configurations are similar in all layers due to the geometry of CDs. Thus repulsion of pancakes inside randomly positioned CDs in the same layer leads to enhancement of c-axis correlations. Another mechanism for pancake alignment inside CDs is magnetic attraction of pancakes in adjacent layers.

In conclusion, we extract the universal phase difference correlation function using measurements of c-axis resistivity as a function of the parallel component of the magnetic field at fixed perpendicular component. We estimated the correlation length of the pancake density correlation function along the c axis as a function of the filling factor f of columnar defects. It first increases with f, reaches a maximum at $f \approx 0.35$, and then drops as pancakes start to occupy positions outside of CDs. We argue that enhancement of the alignment of pancakes inside columnar defects is caused by the interaction of pancakes confined inside columnar defects.

Useful discussions with V. M. Vinokur are greatly appreciated. We thank P. Kes and T.-W. Li for providing Bi-2212 single crystals and R. Olsson for technical assistance. This work was supported by the U.S. DOE.

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