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Angular dependence of *c*-axis magnetoresistance in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with columnar defects

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We measured the angular dependence of the *c*-axis magnetoresistance $\rho_c(\mathbf{B})$ of $Bi_2Sr_2CaCu_2O_{8+\delta}$ irradiated with heavy ions. At temperatures near 69 K the scaling of $\rho_c(\mathbf{B})$ with the *c*-axis magnetic field component $B_\perp$ is broken and the in-plane field, $B_\parallel$, affects ρ_c. At this temperature, at a specific field $B_{cr}\approx B_\Phi/2$, magnetoresistance becomes independent of field orientation. This crossing point allows us to estimate the correlation length L of pancake positions along the c axis. We find $L/s\sim 100$ at $B=B_{cr}$, where s is the interlayer spacing. This provides evidence of strong enhancement of pancake alignment in the vortex liquid in crystals with columnar defects. [S0163-1829(99)14925-7]

The properties of the vortex liquid in high-temperature superconductors, HTS, in the presence of strong disorder is one of the most challenging problems in the physics of the vortex state. It is well established now that in pristine $Bi_2Sr_2CaCu_2O_{8+\delta}$, Bi-2212, crystal vortices form a weakly *c*-axis-correlated pancake liquid. Thermodynamics and intralayer dynamics of this liquid are defined mostly by pancake concentration, i.e., by the *c*-axis magnetic field $B_\perp$.[1] This behavior is, however, strongly affected by the presence of correlated disorder. The most effective pinning centers are produced by heavy ion irradiation. Irradiation of the HTS by energetic ions produces amorphous tracks, where the superconductivity is suppressed. Such columnar defects (CD's), with radii comparable with the superconducting coherence length, are ideal for pinning vortex lines, but their effect on pancake vortices is less obvious. The main questions are (a) are pancake vortices positioned mainly inside columnar defects in the liquid phase?, and (b) are *c*-axis correlations enhanced in the presence of CD's or do they remain similar to that in the liquid phase of pristine crystals?

Important information about the effect of CD's on the pancake liquid was obtained from reversible magnetization measurements.[2] In pristine crystals reversible magnetization M monotonically increases with the magnetic field $B_\perp$. In irradiated crystals, due to gain in pinning energy, penetration of vortices into crystals becomes more favorable than in pristine crystals, and the diamagnetic moment drops in the presence of CD's at low fields $B_\perp \ll B_\Phi$ when all vortices may occupy CD's. However, as $B_\perp$ increases towards the matching field B_Φ, interstitial vortices start to appear, losing the advantage in pinning energy associated with the CD's. This results in a drop of magnetization (i.e., in an increase in the diamagnetic moment) in the field interval between $\approx B_\Phi/4$ and B_Φ. At larger fields the difference between pristine and irradiated crystals almost vanishes. Such an anomaly in $M(B_\perp)$ dependence was observed in the vortex liquid up to rather high temperature, indicating that mobile pancakes, inherent to the vortex liquid, are localized largely onto CD's, even at temperatures close to T_c. Recent study of the vortex-lattice melting in weakly irradiated Bi-2212 also confirmed this picture.[3] However, the thermodynamics of the vortex state depends weakly on *c*-axis correlation of pancakes; it is determined mainly by intralayer interactions, which are much stronger that those associated with the *c*-axis vortex structure.[4,5] For this reason reversible magnetization is determined by pancake concentration and scales with $B_\perp$. Thus magnetization measurements show that pancakes are positioned mainly inside CD's at $B_\perp < B_\Phi/3$ but they do not provide information on *c*-axis correlations of pancakes inside CD's.

In contrast, Josephson interlayer properties of highly anisotropic Bi-2212 are extremely sensitive to the *c*-axis correlations of the pancakes, because Josephson current depends on the interlayer phase difference. Pancakes aligned along the c axis do not contribute to the phase difference, but those shifted due to thermal fluctuations or pinning do. This leads to a larger phase difference in the uncorrelated liquid and thus to the suppression of the *c*-axis superconducting current. Measurements of Josephson plasma resonance (JPR) reveal for the first time that *c*-axis correlation in the vortex liquid in the presence of CD's depends on $B_\perp$ nonmonotonically in the temperature interval 60–69 K, showing enhancement at $B_\perp \sim B_\Phi/3$,[6] while in the liquid phase in pristine crystals correlation drops with $B_\perp$ at all temperatures. Nonmonotonic behavior with $B_\perp$ was found also in the dependence of the *c*-axis resistivity, ρ_c, which is also determined by interlayer Josephson current.[7] Namely, ρ_c in the same temperature interval exhibits an increase with $B_\perp$ at $B_\perp \ll B_\Phi$, a flattening or even a decrease in the field interval between $0.2B_\Phi$ and $0.4B_\Phi$ followed by further increase of ρ_c at higher $B_\perp$. Unfortunately, neither JPR nor $\rho_c(B_\perp)$ measurements provide sufficient information to estimate the enhancement of the *c*-axis correlation quantitatively.

It was shown in Refs. 8 and 9 that dependence of JPR frequency and ρ_c on the parallel component of the magnetic field provides complete information about *c*-axis phase correlations. Based on this idea, in this paper we study the angular dependence of ρ_c at different orientations of the magnetic field B in the correlated pancake liquid phase in the presence of CD's. We show that scaling with $B_\perp$ is absent in this phase. Moreover, we found, that at $B=B_{cr}\approx B_\Phi/2$, this angular dependence is accurately compensated, providing a crossing point where ρ_c is independent of the orientation θ of the magnetic field with respect to the crystal c axis over a wide range of θ. Such an anomaly gives an opportunity to estimate the correlation length of pancake positions along the c axis at the crossing field.

For our experiments high quality Bi-2212 crystals ($T_c \simeq 85$ K) of about $1\times1.5\times0.02\,\mathrm{mm}^3$ were used. The irradiation by 1.2 GeV U^{238} ions was performed on the ATLAS accelerator (Argonne National Laboratory). According to TRIM calculations these high energy ions produce in Bi-2212 crystals continuous amorphous tracks with diameter 4–8 nm and length 25–30 μm. Below we present the results for samples irradiated with an effective density of columnar defects corresponding to the matching field $B_\Phi=1$ T. Another pristine sample was used as a reference. We checked also several crystals from a different synthesis for universality of the obtained results.

Our measurements were performed using a warm bore insert in a liquid helium cryostat with a $9T$ superconducting magnet, and also in a liquid nitrogen (LN) Dewar installed into an electromagnet that provides a magnetic field up to 1 T. The sample was attached to a sample holder with goniometric stage, allowing rotation of the sample with respect to the applied field with an accuracy of about $\pm0.1°$. The sample was immersed in a LN bath in order to provide accurate temperature stabilization and to avoid heating effects. Magnetic fields applied along the c axis of the sample were monitored by a Hall sensor attached to the sample stage. Two pair of silver contact pads were deposited on both sides of the samples for standard 4-probe transport measurements and fine gold leads were attached using silver epoxy. The resistivity for the contact pair at room temperature was about $1-3\,\Omega$. We measured R_c as a function of applied magnetic field B at different angles θ with respect to the c-axis of the crystal (see inset in Fig. 1).

In Fig. 1 we present the normalized magnetoresistance $\tilde{\rho}_c\equiv\rho_c/\rho_n$ as a function of applied field along the c axis measured at $T=69.5$ K. Here ρ_n is the normal state resistivity at $T=120$ K. This procedure allows us to cancel the geometrical factors, which are difficult to measure accurately for the small samples. Note that this normalization does not affect further considerations because only relative changes of ρ_c are important. After the sharp onset at the irreversibility line, $\tilde{\rho}_c$ for irradiated crystals displays a pronounced dip due to enhanced vortex correlation associated with filling of the CD's reported in Ref. 7. As applied field increases further on, magnetoresistance continues to increase gradually. In the pristine crystal the resistance increases with $B_\perp$ monotonically.

In the left panel of Fig. 2 the family $\tilde{\rho}_c$ vs B at different angles is presented. The magnetoresistance decreases with the angle at $B>B_\Phi/2$ (as in the pristine crystals), reflecting a decrease of $B_\perp$, but *increases* with the angle at low fields

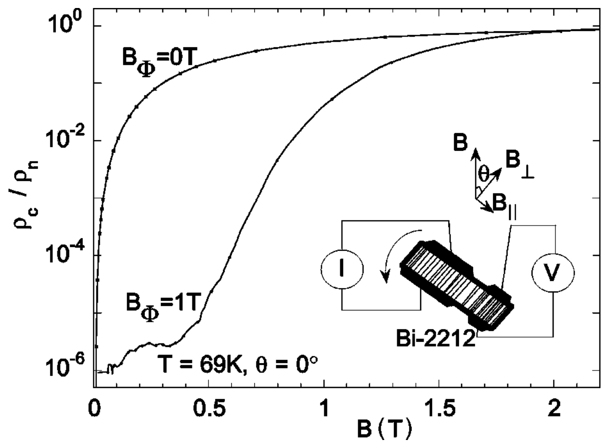

FIG. 1. Dependence of c-axis magnetoresistance $\tilde{\rho}_c$ on the c-axis magnetic field for pristine ($B_\Phi=0$), and irradiated ($B_\Phi=1T$) crystals. The latter displays a dip due to enhanced vortex correlations in the pancake liquid. Inset: schematic experimental setup.

($0.1B_\Phi<B<B_\Phi/2$), in the region where reentrant enhancement of c-axis correlation was observed in $\rho_c(B_\perp)$ dependence.

In our experiment the inclination of the sample in the applied field results in two effects: decrease of the c-axis field $B_\perp=B\cos\theta$ and increase of the in-plane field $B_\parallel=B\sin\theta$. In order to separate these two effects we present $\tilde{\rho}_c$ as a function of the c-axis component $B_\perp$ in the right panel of Fig. 2. The magnetoresistance of the sample scales with $B_\perp$ at low and at high fields. However, in the range $B_\Phi/4<B<B_\Phi$ this *scaling is broken*. This anomalous behavior occurs in the range of field and temperature where enhanced vortex correlations in the pancake liquid were observed in JPR and in $\rho_c(B_\perp)$.

In Fig. 3 we blow up the region where the scaling is broken. It is clearly seen on the right panel that $\tilde{\rho}_c$ here depends on the in-plane field, increasing gradually with $B_\parallel$. The most outstanding feature can be seen in the left panel of Fig. 3. Here $\tilde{\rho}_c$ curves at different angles are presented as a function of B. They all cross at a single point, which we denote as B_{cr} (small scattering of the data will be commented below). This crossing point is observed for all the crystals which display the dip of ρ_c. It means that at $B=B_{cr}$, *angular dependence of magnetoresistance practically vanishes*, i.e., decrease of ρ_c due to decrease of $B_\perp$ is accurately compensated by increase of the magnetoresistance with increasing $B_\parallel$. Such an unusual behavior of ρ_c originates from the enhanced correlations developing in the vortex liquid in the presence of the CD's. This effect can be explained in the framework of the approach developed in Refs. 8 and 9 and will be used below to estimate quantitatively the characteristic length R_1 of the phase difference in-plane correlation function.

Let us first discuss how the in-plane field component affects the c-axis magnetoresistance. An approach developed initially for the field behavior of JPR frequency[8] was extended recently for c-axis transport properties.[9] In Josephson coupled superconductors in the presence of a c-axis current, the voltage $V_{n,n+1}$ is induced by slips of the phase difference $\varphi_{n,n+1}(\mathbf{r},t)$ between the layers n and $n+1$, as described by

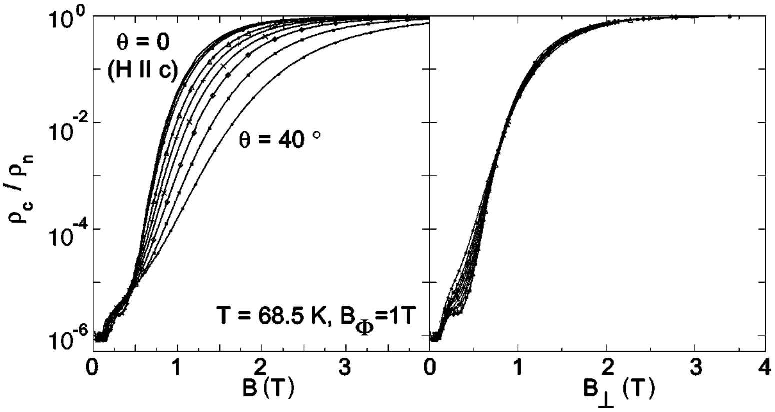

FIG. 2. Dependence of $\tilde{\rho}_c$ on the magnetic field B for different θ, with step 5° from 0° to 40° (left). The same data plotted as a function of the c-axis magnetic field $B_\perp$ (right). The scaling of $\tilde{\rho}_c$ with $B_\perp$ is broken in the correlated vortex liquid.

the Josephson relation $V_{n,n+1}=(\hbar/2e)\dot{\varphi}_{n,n+1}$. Here $\mathbf{r}=x,y$ are coordinates in the ab plane, and t denotes the time. The c-axis conductivity in the vortex liquid state $\sigma_c=1/\rho_c$ is determined by the Kubo formula[10]

$$\sigma_c(B_\perp,B_\parallel)=(s\mathcal{J}_0^2/2T)\int_0^\infty dt\int d\mathbf{r}\,S(\mathbf{r},t), \tag{1}$$

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

where $\mathcal{J}_0$ is the Josephson critical current, s is the interlayer distance, and $\langle\cdots\rangle$ means thermal average and average over disorder. Time variations of the phase difference are caused mainly by mobile pancakes[11] induced by $B_\perp$, while the parallel field component induces a stationary phase difference in the lowest order in Josephson coupling. We split $[\varphi_{n,n+1}(\mathbf{r},t)-\varphi_{n,n+1}(0,0)]$ 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

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

In a single pointlike junction the phase difference induced by $B_\parallel$ results in the Fraunhofer pattern of Josephson critical current as a function of the magnetic field parallel to the junction. In our case of a multilayer superconductor the phase difference induced by $B_\parallel$ interferes with that induced by pancakes. Thus we obtain

$$\sigma_c(B_\perp,B_\parallel)=(\pi s\mathcal{J}_0^2/T)\int dr\,r\tilde{G}(r,B_\perp)J_0(\alpha B_\parallel r),$$

$$\tilde{G}(r,B_\perp)=\int_0^\infty dt\,S(r,t,B_\perp), \tag{4}$$

where $J_0(x)$ is the Bessel function, $\alpha=2\pi s/\Phi_0$ (Φ_0 is a flux quantum), and the function $\tilde{G}(\mathbf{r},B_\perp)$ depends on correlations of the phase difference induced by pancake vortices. For small $B_\parallel$ (small angles) we expand the Bessel function in $B_\parallel$:

$$\sigma_c(B_\perp,B_\parallel)\approx\sigma_c(B_\perp,0)\left[1-\frac{1}{4}\alpha^2R_1^2(B_\perp)B_\parallel^2\right],$$

$$R_1^2(B_\perp)=\int dr\,r^3\tilde{G}(r,B_\perp)\bigg/\int dr\,r\tilde{G}(r,B_\perp). \tag{5}$$

Here the in-plane correlation length $R_1(B_\perp)$ describes the decay of the phase difference correlation function. When pancakes are positioned mainly inside CD's, the characteristic length of this decay, R_1, gives direct information on the c-axis correlation of pancake positions because the drop of the phase difference correlations in the ab plane is caused by interruptions in the pancake arrangement along CD's.[8] The characteristic length, L, of the pancake density correlation function is related to R_1 as $L/s\approx R_1^2/10a^2$, where $a=(\Phi_0/B_\perp)^{1/2}$ is the intervortex distance.[9] This expression and Eq. (5) are key points for further discussion.

It is clear from Eq. (5) that generally σ_c depends upon both components of the field. However, in an uncorrelated liquid, when $R_1\approx a$, the effect of the in-plane field is small and can be observed only in high fields $B_\parallel\gtrsim\Phi_0/sa$. As a

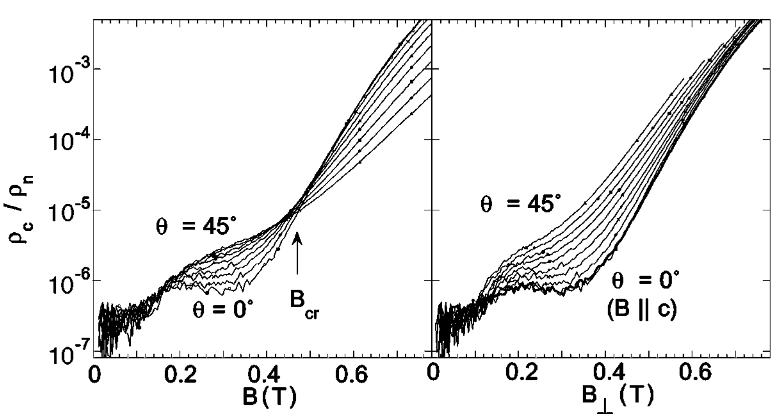

FIG. 3. Blowup of the anomaly for the irradiated crystal. Dependence of $\tilde{\rho}_c$ on magnetic field B (left) and on the c-axis magnetic field $B_\perp$ (right). θ increases from 0° to 45° with step 5°. The crossing point B_{cr}, is marked by the arrow on the $\tilde{\rho}_c$ vs. B panel.

result, in the uncorrelated pancake liquid the c-axis conductivity scales with $B_\perp$ in fields $B \ll \Phi_0/sa$. For an irradiated sample, as filling of CD's progresses, vortices start to form stacks and the correlation length R_1 significantly exceeds a, reaching a maximum value near $B_\Phi/3$. Here the effect of the in-plane field becomes significant and scaling of magnetoresistance with $B_\perp$ breaks. As the field $B_\perp$ further increases, the fraction of the interstitial vortices increases. These vortices introduce additional disorder to the system which results in decay of correlations, in reduction of R_1 down to $\sim a$ and, consequently, the effect of $B_\parallel$ drops. Then, at elevated fields above B_Φ scaling of ρ_c with $B_\perp$ is restored. This scenario describes qualitatively well our experimental results.

Now we show that the crossing point in Fig 3 allows us to estimate the correlation radius $R_1(B_{cr})$. Using Eq. (5) for the variation of σ_c at small angles we expand as

$$\delta\sigma_c(B_\parallel, B_\perp) \approx \frac{\partial^2 \sigma_c}{\partial B_\parallel^2} \frac{(\delta B_\parallel)^2}{2} + \frac{\partial \sigma_c}{\partial B_\perp} \delta B_\perp . \tag{6}$$

Substituting $B_\parallel \approx B\theta$ and $B_\perp \approx B(1-\theta^2/2)$ we obtain

$$\delta\sigma_c(B_\parallel, B_\perp) \approx \frac{1}{2} B \left(\frac{\partial^2 \sigma_c}{\partial B_\parallel^2} B - \frac{\partial \sigma_c}{\partial B_\perp} \right) (\delta\theta)^2. \tag{7}$$

Note that data presented in Fig. 2 and Fig. 3 are measured up to rather large angles. Thus our small angle approximation is not accurate there and the data start to deviate from the crossing point. Also small temperature deviations contribute in data scattering. Independence of σ_c on the angle θ at B_{cr} occurs when the expression in the brackets becomes zero. With the help of Eq. (5) we obtain the correlation radius R_1:

$$R_1^2(B_{cr}) = -\frac{1}{2B_{cr}} \frac{\Phi_0^2}{\pi^2 s^2} \left[\frac{\partial \ln \sigma_c(B_\perp, 0)}{\partial B_\perp} \right]_{B_\perp = B_{cr}} . \tag{8}$$

From the data presented in Fig. 3, we obtain $(\ln \sigma_c(B_\perp,0))' \approx -23T^{-1}$ at $B = B_{cr} \approx 0.47T$. Using Eq. (8) we calculate $R_1/a \approx 32$. This value is larger than the result obtained in Ref. 9, where $R_1 \sim 10a$ was found, but still in reasonable agreement with it. Thus the correlation length L of pancake positions along the c axis is $\approx 100s$. The difference in the correlation lengths from the previous estimations[9] can be due to sample differences. The sample studied in this work has a more pronounced dip in the ρ_c vs H dependence, which indicates stronger correlations.

We would like to emphasize the difference between our observation and results obtained in flux-transformer geometry.[12] In those latter experiments current was applied to the top surface of the sample and voltage was measured in both the top and bottom layers. In some range of the magnetic fields and temperatures top and bottom voltages coincide, indicating a similar motion of vortices in all layers. This was considered as evidence of pancake coupling along the c axis. Unfortunately, the situation here is rather complicated because of mixing of the in-plane and c-axis resistivities. Namely, the current applied along the top layer penetrates deep into the sample along the c axis and flows along the bottom layer as well as along the top layer. This results in a similar motion of the pancakes through the full sample thickness, even without c-axis correlation provided ρ_c is small enough. As we have shown, the c-axis transport measurements as a function of in-plane field component are free of this additional effect and are very sensitive to pancake correlation between adjacent layers.

To conclude, we have presented evidence for the presence of a partially aligned vortex liquid in irradiated Bi-2212 from the angular dependence of c-axis magnetoresistance. In the range of temperatures and magnetic fields where c-axis correlations develop, interlayer transport becomes much more sensitive to the in-plane component of the magnetic field in comparison with the uncorrelated liquid in pristine crystals. Then scaling of ρ_c with $B_\perp$ breaks, and, at the field B_{cr}, angular dependence becomes very weak. From this crossing point we estimate the c-axis correlation length of pancake positions $L/s \approx 100$ at $B_\perp \approx B_\Phi/2$. The origin of this alignment can be due to magnetic intralayer interaction of pancakes which favors similar filling of CD's due to their geometry. However, an additional effect of interlayer magnetic interaction of pancakes cannot be excluded yet.

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