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Entanglement of Solid Vortex Matter: A Boomerang Shaped Reduction Forced by Disorder in Interlayer Phase Coherence in $Bi_2Sr_2CaCu_2O_{8+y}$

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We present evidence for entangled solid vortex matter in a glassy state in a layered superconductor $Bi_2Sr_2CaCu_2O_{8+y}$ containing randomly splayed linear defects. The interlayer phase coherence—probed by the Josephson plasma resonance—is enhanced at high temperatures, reflecting the recoupling of vortex liquid by the defects. At low temperatures in the vortex solid state, the interlayer coherence follows a boomerang-shaped reentrant temperature path with an unusual low field decrease in coherence, indicative of meandering vortices. We uncover a distinct temperature scaling between in-plane and out-of-plane critical currents with opposing dependencies on field and time, consistent with the theoretically proposed "splayed-glass" state.

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Entangled states of matter are likely in physical systems where disorder is ubiquitously present. A widely considered example is that of one dimensional (1-D) elastic strings subject to random or correlated defects [1]—a situation encountered in environments as disparate as directed polymers [2], magnetic domain walls [3], fire fronts [4], or vortex lines in superconductors [5]. The last presents a rich laboratory for exploring the intricate competition between the vortex interactions, fluctuations, disorder effects, and the ability to cut and reconnect—all ultimately informing the state of coherence and entanglement of lines.

In high transition temperature (T_c) superconductors, the competing influences lead to new states of vortex matter. Bragg glass [6] with quasi-long-range translational order can arise in the presence of weak point defects, while a conceptually different Bose glass state [7] is promoted by topologically correlated columnar defects (CDs), where the vortices become unidirectionally localized. Another distinct "splayed glass" state has been predicted [8] in the presence of directionally distributed CDs; this state differs dynamically from other glassy states, with forced entanglement of vortex lines by the splayed CDs as its chief characteristic.

The differentiating factor and a key to the nature of these states reside in the longitudinal vortex correlations. In layered superconductors, the quasi 2-D pancake vortices in the layers are connected by Josephson strings to form the lines. There, vortex correlations are closely related to the interlayer phase coherence (IPC) $\langle\cos\phi_{n,n+1}\rangle$, with $\phi_{n,n+1}$ being the gauge-invariant phase difference between the neighboring layers n and $n+1$. IPC can be directly probed by Josephson plasma resonance (JPR) [9, 10, 11, 12], with resonance frequency ω_p given by

$$\omega_p^2(H,T) = \omega_p^2(0,T)\langle\cos\phi_{n,n+1}\rangle = \frac{8\pi^2 cs}{\epsilon_0\Phi_0}J_c^c, \quad (1)$$

where s is the interlayer spacing, ϵ_0 the dielectric constant, Φ_0 the flux quantum, and J_c^c the c-axis critical current density.

In pristine $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO), it has been demonstrated [13, 14] that the IPC suddenly decreases with field at the phase transition between the low-field Bragg glass and the high-field liquid phases, and that within the liquid phase vortices in each layer are well decoupled [15]. In BSCCO with the unidirectional CDs, known for their strong vortex pinning [16, 17], an enhanced IPC has been observed in the liquid state near $B_\Phi/3$ (B_Φ is the matching field where the vortex density coincides with the defect density) [18, 20, 21, 22]. Thus, the decoupled vortex liquid transforms to a recoupled liquid state at higher fields, where the vortices tend to be confined and forced to align along the CDs. Forced topological entanglement has been deduced from transport in the liquid state of $YBa_2Cu_3O_7$ [23], where strong interlayer coupling prevents experimental access to IPC. In more anisotropic BSCCO [24] and Hg-based systems [19], partial evidence for entanglement has been claimed from large critical current enhancements in polycrystalline samples with splayed CDs. Thus far, however, there is no direct demonstration of entangled vortex structure via IPC.

Here we report on the IPC in BSCCO single crystals containing directionally distributed CDs. We demonstrate that the interlayer coherence in BSCCO with uniformly *splayed* CDs shows an anomalous 'boomerang'-like reduction at low temperatures and low fields. The forced entanglement is evidenced by the enhanced in-plane critical current density J_c^{ab} with the concurrent drop of J_c^c—the latter being a measure of vortex meandering. The found anticorrelation of the field and time dependence of J_c's in the boomerang region of the phase space is in correspondence with the proposed framework in the splayed glass state [8].

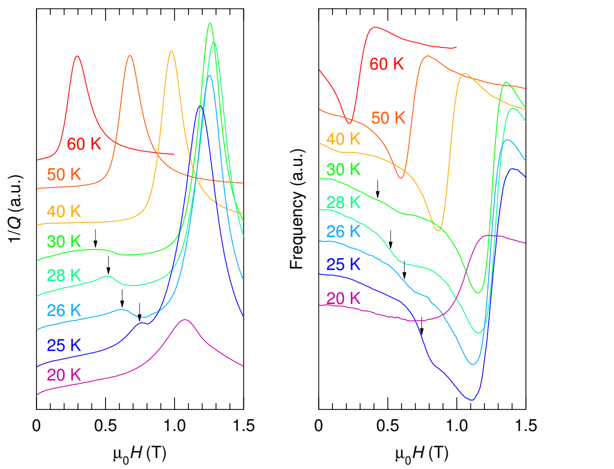

FIG. 1: (color online). Microwave dissipation $1/Q$ (left) and frequency shift (right) of the 28-GHz Cu cavity including the BSCCO crystal with splayed CDs ($B_\Phi \approx 1$ T) as a function of H applied parallel to the c axis. Each curve is vertically shifted for clarity. Arrows mark the second resonance.

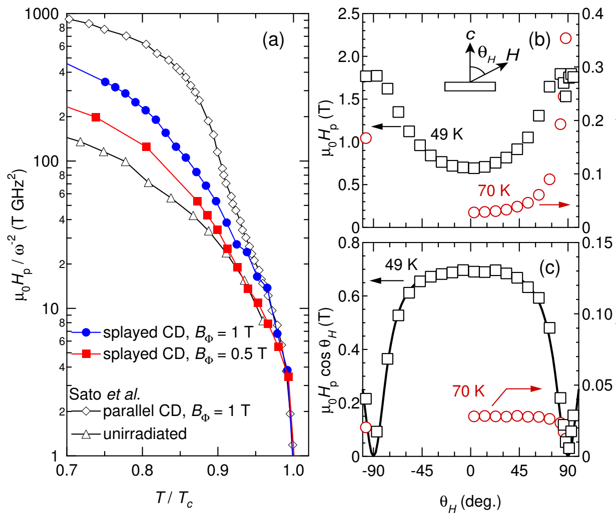

FIG. 2: (color online). (a) Resonance field H_p normalized by ω^{-2} as a function of T/T_c for $B_\Phi \approx 1$ T (solid circles) and 0.5 T (solid squares) compared with those of pristine (open triangles) and heavy-ion irradiated BSCCO with $B_\Phi = 1$ T (open diamonds) [18]. (b) Angle dependence of H_p for the high-field state at 49 K (squares) and for the low-field state at 70 K (circles). θ_H is the angle between the applied field and the c axis. (c) c-axis component of H_p vs. θ_H. The solid line is a fit to Eq. (2) with $\gamma = 400$ and $A = 0.47$ deg.

Optimally-doped BSCCO single crystals were prepared by the floating zone method. Crystals with thicknesses (along the c axis) of ~ 20 μm were exposed to 0.8 GeV proton beam in Los Alamos Neutron Science Center (LANSCE). Bi nuclei within the crystals are fissioned by collisions with swift protons and the fission fragments create extended randomly oriented damage tracks with diameter of ~ 7 nm and length of ~ 6 μm [24]. In this study, we used two crystals with matching fields $B_\Phi \approx 0.5$ and 1 T, as estimated from the relation between areal defect density and the proton fluence [24]. JPR experiments were performed by a cavity perturbation technique at a frequency $\omega/2\pi \approx 28$ GHz [11, 13, 18], from which we evaluate J_c^c by Eq. (1). Standard magnetization measurements were used to determine the creep rate $S = -\mathrm{d}\ln(J_\mathrm{c}^{ab})/\mathrm{d}\ln(t)$ as well as J_c^{ab} as a function of field and time [19].

Josephson Plasma Resonance.— Figure 1 shows the field dependence of the inverse quality factor $1/Q$ ($\propto$ microwave dissipation) and the frequency shift for the $B_\Phi \approx 1$ T sample. Magnetic field H is increased after the zero-field-cooling condition. Clear JPR is observed as a peak in $1/Q$ and a step-like change in the frequency shift. At high temperatures, we always observe a single resonance line, in contrast to the case of BSCCO with parallel CDs along the c axis, where multiple resonances have been observed near $B_\Phi/3$ [18, 20, 21].

At low temperatures, in addition to the main resonance line, we find another resonance (indicated by the arrows) at a lower field. In this second resonance, the frequency shift shows a step-like anomaly having an *opposite* direction from that of the main resonance. This goes to prove that the second resonance does not originate from some secondary low-T_c phase or inhomogeneity, but is an intrinsic feature of this system, as will be discussed later.

High-Temperature Liquid State.— Let us first discuss the single resonance in the liquid state at high temperatures. Figure 2(a) shows the temperature dependence of the resonance field H_p. To compare this with previous reports [18], we normalize the temperature T by T_c and H_p by ω^{-2} [9, 13]. Near T_c, our data roughly follow the data for pristine BSCCO as well as for the one with parallel CDs [22]. However, at low T and high fields a distinct deviation is observed, indicating that the IPC in the system with randomly splayed CDs is enhanced relative to the pristine one. A quantitative comparison with a system containing the parallel CDs with the same B_Φ shows that the IPC enhancement in our case is considerably smaller. Moreover, we do not observe multiple resonances in the liquid state, which are only expected for largely enhanced IPC with non-monotonic field dependence of $\langle\cos\phi_{n,n+1}\rangle(H)$ [25].

The angular field dependence is particularly telling. In BSCCO with CDs parallel to the c axis, it has been shown that in the *low-field decoupled* liquid state, the resonance field is determined mostly by the c-axis component over a wide range of field angles [20]. By contrast, in the *high-field recoupled* liquid state H_p is nearly angle-independent; indeed, this is a key signature of recoupling. Our low-field data at 70 K in Fig. 2(b) reproduces the previous results on the low-field decoupled liquid state; its c-axis component $H_\mathrm{p}\cos\theta_H$ is almost constant over a wide angle range. On the other hand, the high-field data

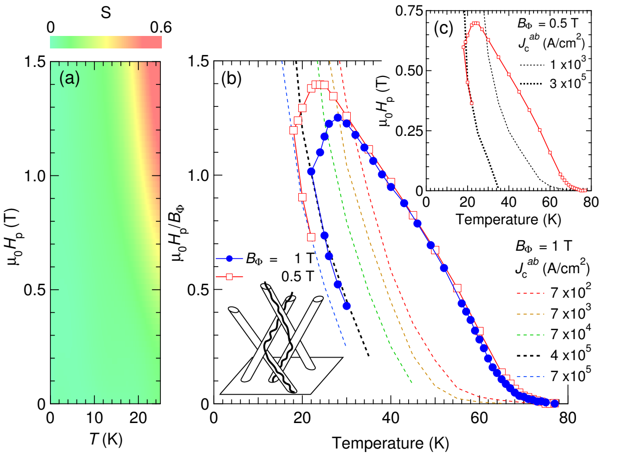

FIG. 3: (color online). (a) Contour map of the creep rate S in H-T plane. (b) Temperature dependence of H_p normalized by B_Φ [27]. Also shown are the contours of in-plane J_c^{ab} (dashed lines) for $B_\Phi \approx 1$ T sample. Sketch of splayed defects and entangled vortices is also shown. (c) Temperature dependence of H_p together with J_c^{ab} contours for $B_\Phi \approx 0.5$ T sample.

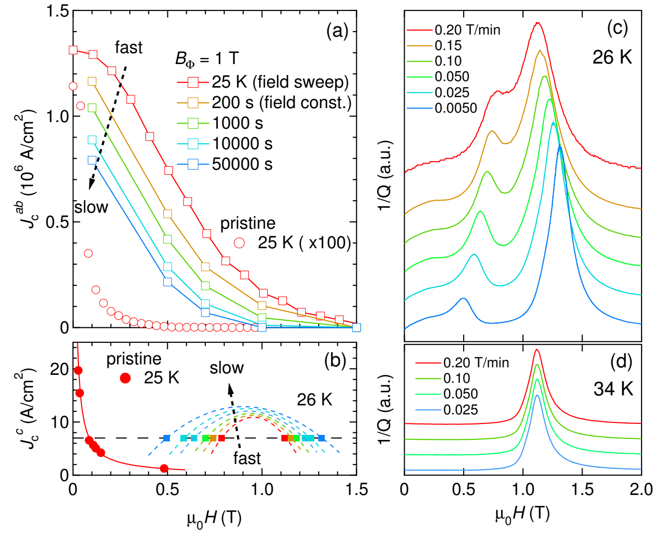

FIG. 4: (color online). (a) In-plane J_c^{ab} as a function of field at different times for $B_\Phi \approx 1$ T (squares) and pristine samples (circles). (b) Field dependence of c-axis J_c^{c} for $B_\Phi \approx 1$ T (squares) with different field sweep rates shows a sharp contrast to the monotonic $J_\mathrm{c}^{c}(H)$ in a pristine crystal [13] with smaller interlayer coupling (circles). Our measurement frequency corresponds to $J_\mathrm{c}^{c} \approx 7$ A/cm^2. The lines are guides for the eyes. The JPR fields change with the sweep rate at 26 K (c) but stay constant at 34 K (d). The two resonances for each rate in (c) correspond to the two points in (b) in the same color [27]. In (c) and (d) data are shifted vertically.

at 49 K shows an odd behavior; neither H_p nor $H_\mathrm{p}\cos\theta_H$ are angle independent [Figs. 2(b) and (c)].

To analyze this, we apply anisotropic scaling procedure [19, 26] to the distribution of splayed CDs. The polar angle θ from the c axis in anisotropic superconductors with anisotropy parameter $\gamma = (m_c/m_{ab})^{1/2}$ can be transformed into $\tilde{\theta}$ in the scaled isotropic system by $\gamma \tan\tilde{\theta} = \tan\theta$. The angle dependence of the trapping probability of vortices in the scaled isotropic system is described by a Lorentz function $P(\tilde{\theta}_H) = 1/(1+(\tilde{\theta}_H/A)^2)$, where the parameter A related to the accommodation angle is determined by the pinning strength of the defects [25]. In our splayed system, the directions of the CDs are random and the angular dependence of the probability in the anisotropic system is described by

$$P(\theta_H) = \int_0^{2\pi}\int_0^{\pi/2} \frac{\sin\theta_\mathrm{CD}\mathrm{d}\theta_\mathrm{CD}\mathrm{d}\phi_\mathrm{CD}}{1+(\tilde{\theta}_{H-\mathrm{CD}}/A)^2}. \qquad (2)$$

Here θ_CD is the polar angle between a CD and the c axis, and ϕ_CD is its angle of longitude with respect to the field rotation plane. Relative angle between the field and the defect in the scaled isotropic system is given by $\tilde{\theta}_{H-\mathrm{CD}} = \cos^{-1}(\sin\tilde{\theta}_H \sin\tilde{\theta}_\mathrm{CD}\cos\tilde{\phi}_\mathrm{CD} + \cos\tilde{\theta}_H\cos\tilde{\theta}_\mathrm{CD})$ with $\tilde{\theta}_H = \tan^{-1}(\tan\theta_H/\gamma)$, $\tilde{\theta}_\mathrm{CD} = \tan^{-1}(\tan\theta_\mathrm{CD}/\gamma)$, and $\tilde{\phi}_\mathrm{CD} = \phi_\mathrm{CD}$. As shown in Fig. 2(c), the c-axis component of the resonance field at 49 K can be fitted to Eq. (2) with parameters physically sensible [25]. Thus, in the high-field liquid state vortices are largely trapped inside the CDs. We conclude then that here a recoupling crossover takes place in a field range much smaller than the matching field B_Φ, much akin to the recoupling induced by parallel CDs.

Low-Temperature Glass State.— In Fig. 3(b) we plot the temperature dependence of H_p normalized by B_Φ for both samples. At high temperatures the two curves coincide, indicating that the IPC in this system is mostly determined by the defects. At low temperatures below ~ 30 K, $H_\mathrm{p}(T)$ undergoes a kink and then turns to decrease. This kink is consistent with previous reports in BSCCO [10], where $H_\mathrm{p}(T)$ in the vortex solid state drops almost linearly with decreasing T in the zero-field-cooling condition. Remarkably, $H_\mathrm{p}(T)$ in our system has an anomalous *reentrant* behavior—it is this boomerang-like trajectory that gives double resonance lines in single field sweep runs at temperatures below ~ 30 K [27].

Since we use a fixed microwave frequency and $\omega_\mathrm{p}(0,T)$ in Eq. (1) is only weakly temperature dependent at low temperatures [13], the resonance field curve $H_\mathrm{p}(T)$ provides a rough contour of IPC at low temperatures. Thus, the observation of the reentrant behavior at low temperatures in this system demonstrates that the field dependence of $\langle\cos\phi_{n,n+1}\rangle$ at a fixed temperature is nonmonotonic [see also $J_\mathrm{c}^{c}(H)$ in Fig. 4(b)]: at low fields it increases with field and at high fields it decreases. The observed opposite steps at the two resonances in the frequency shift in Fig. 1 are in accord with this result.

More importantly, $H_\mathrm{p}(T)$ at low fields follows a contour of in-plane $J_\mathrm{c}^{ab} \approx$ 3-4 $\times 10^5$ A/cm^2 [Figs. 3(b) and (c)] as well as of the creep rate S [Fig. 3(a)]. This newly found scaling can be naturally understood when the meandering vortex structure (witnessed by the low H_p) facilitates its pinning and reduces the vortex dynamics.

In the proposed "splayed glass" phase [8], vortices entangle by confining their finite segments to different columnar paths [see sketch in Fig. 3(b)]. The dynamics is determined by the nucleation and the motion of kinks, which are impeded from sliding along the CDs at the crossing sites when the CDs are roughly localization length apart [8, 28]. In the uniformly splayed CD landscape, random exchanges of vortex lines with numerous kinks will show up as a reduction of IPC, which is proportional to J_c^c [see Eq. (1)].

In Figs. 4(a) and (b), we compare $J_\mathrm{c}^{ab}(H)$ and $J_\mathrm{c}^c(H)$ with those in the pristine samples. From the boomerang $H_\mathrm{p}(T)$ in Fig. 3, at a fixed temperature we expect a non-monotonic $J_\mathrm{c}^c(H)$. Indeed, in sharp contrast with the pristine samples, at low fields J_c^c decreases with decreasing H [dashed lines in Fig. 4(b)]. Concurrently, the inplane J_c^{ab} rapidly increases, fast exceeding that of pristine one. We remark that this J_c anti-correlation is counterintuitive in a coupled pancake system and unique to the splayed glass phase [29]. In pristine BSCCO, the reduction of longitudinal correlation due to decoupling is a consequence of in-plane correlations becoming dominant at higher fields. We also note that in the Bose glass state discussed in the system with parallel CDs such an anti-correlation between J_c^c and J_c^{ab} is not expected. Thus the low-field J_c^c reduction discovered in our system is anomalous.

Also striking is that the two resonance lines split apart [Fig. 4(c)]—a slower field-sweep rate gives rise to a larger J_c^c [Fig. 4(b)]. We emphasize that the time relaxation of J_c^{ab} shows an opposite trend [Fig. 4(a)]. All these findings are characteristics of splayed glass.

Thus, through our experiments we demonstrate unusual 'line' behaviors in a system with randomly oriented linear defects. The non-monotonic field dependence of $\langle\cos\phi_{n,n+1}\rangle$, the reentrant "boomerang" path of the JPR field, the scaling of this path in the H-T phase space with the contours of iso-J_c^{ab}, all support a strong low-field suppression of interlayer phase coherence. While a full theory of $\langle\cos\phi_{n,n+1}\rangle$ in a system of random distributions of CDs that includes point disorder is yet to be formulated, our findings in vortex structure and dynamics support the presence of a distinct "splayed glass" entangled state of matter.

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