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Annealing of transient vortex states near the order-disorder phase transition in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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High-temporal resolution magneto-optical measurements in $Bi_2Sr_2CaCu_2O_{8+\delta}$ demonstrate that transient vortex states govern its magnetic behavior near the order-disorder vortex phase transition. These data enable direct measurement of the annealing time τ of the transient states as a function of the induction, temperature, and electric field. The behavior of τ reveals fundamental limitations of common experimental procedures in characterizing the disorder-driven vortex phase transition.

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Recent studies of the vortex matter in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) showed that transient disordered vortex states affect transport and magnetic measurements near the vortex order-disorder phase transition.[1–3] These transient states are inadvertently created by injection of vortices through inhomogeneous surface barriers,[1] or by "supercooling" of the disordered vortex phase while the external magnetic field is decreased.[3] Special experimental procedures have been devised to eliminate the transient effects, aiming to reveal the actual underlying vortex matter properties.[1,4] However, less attention has been devoted to the characterization of the vortex transient states, in order to determine the extent of their influence in terms of field range, temperature, and time. An important parameter characterizing the transient vortex states is their lifetime τ as a function of the induction B, temperature T, and electric field E. As shown in Ref. 5, knowledge of τ is essential for correct interpretation of experiments, aiming at characterization of the disorder-induced vortex phase transition. In a previous work[5] we measured τ indirectly by tracing generation of transient disordered vortex states in field sweeping experiments.[6] In this paper we employ a high-speed magneto-optical (MO) system to image the annealing process of transient disordered vortex states, and utilize these data to directly measure the lifetime τ as a function of B, T, and E. Direct observation of the annealing process demonstrates the key role of τ in explaining a series of peculiar phenomena observed in BSCCO, such as the apparent termination of the measured order-disorder transition line below ~ 16 K[7–9], distortion of the first-order nature of the transition in magnetic measurements,[4] and apparent time-dependent effects associated with the transition.[10–13]

Measurements were performed on a $1.55\times 1.25\times 0.05$ mm^3 $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal ($T_c=92$ K). The crystal was grown using the traveling solvent floating zone method.[14] This crystal was specially selected for its uniformity of flux penetration and was checked by magneto-optical imaging before and after it was cut into a rectangle. The external magnetic field H was raised abruptly to a target value between 140 and 840 G with rise time <50 ms. Immediately after reaching the target field, MO snapshots of the induction distribution across the sample surface were recorded at time intervals of 40 ms for 4 s, and 200 ms for additional 26 s, using iron-garnet MO indicator with in-plane anisotropy[15] and a high-speed charge-coupled device (CCD) camera. This procedure was conducted at several temperatures between 20 and 25 K. The spatial resolution of the presented MO data is 4 μm/pixel.

From the MO images we extract profiles showing the time evolution of the induction distribution across the sample width. For a certain location x_0 along the sample width, we extract the local $j\sim dB/dx$ at different times for all measured external fields, and plot it versus the local B. dB/dx is evaluated over a length of 31 μm. Typical results, measured at 21 K, are presented in Fig. 1 for $x_0=-514$ μm measured from the sample center. In the figure, data points corresponding to different times are marked by different symbols, and the solid lines connect all points measured at the same indicated time. Each curve may be considered as an instantaneous local magnetization curve, and the set of curves demonstrates the time evolution of a Dynamic Second Magnetization Peak (DSMP): At short times ($t<0.5$ s), no DSMP is observed. A trace of a DSMP first appears at $t\sim 0.52$ s, and it continues to develop with time, while its onset shifts to higher inductions (from 200 G at 0.52 s to 360 G at 29 s). Similar results have previously been observed in various local and global measurements.[8–13,16] However, the results presented here, originating from high-resolution local magnetic measurements, reveal the central role played by transient vortex

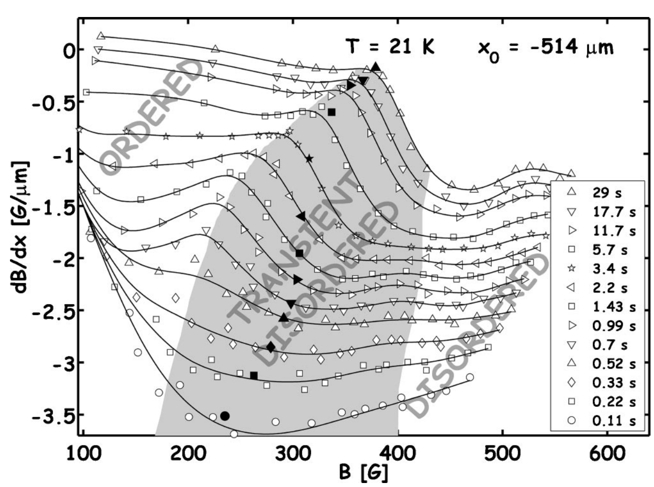

FIG. 1. Typical $dB/dx\sim j$ vs local B at $x_0=-514$ μm for the indicated times. Bold symbols describe the time dependence of dB/dx after applying external field of 465 G. Bold data points are derived from the profiles in Fig. 2. Gray area marks the transient state zone.

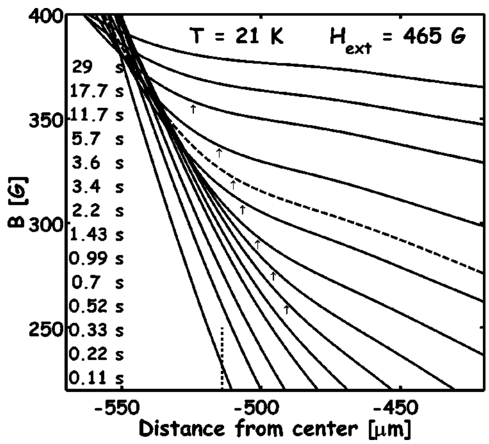

FIG. 2. Time evolution of the magnetic induction profiles at $T=21$ K, after a step increase of the external magnetic field to 465 G. Arrows mark breaks in the profiles. The dotted line indicates the location $x_0=-514$ μm for which Fig. 1 is plotted. Note that the break moves towards the edge, crossing x_0 at about 3.6 s. The profile for $t=3.6$ s is described by the dashed line.

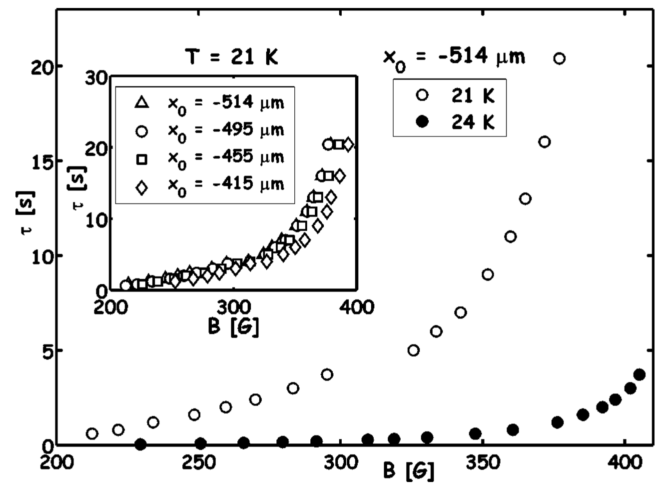

FIG. 3. Lifetime spectrum $\tau(B)$ of transient disordered states for $T=21$ and 24 K, for $x_0=-514$ μm. Inset: Lifetime spectrum of transient disordered states at $T=21$ K, for different locations along the sample.

states in determining the dynamics of the DSMP.[16] Our local magnetic measurements permit clear identification of transient vortex states. The key indicator to the existence of such states is the appearance of a time-dependent sharp change (''break'') in the slope of the induction profile, pointing to coexistence of two distinct vortex states: quasiordered and disordered states, characterized by low and high persistent current, respectively,[2] see Fig. 2. The figure shows the time evolution of the induction profiles after abruptly increasing the external field H from 0 to 465 G. Initially, the profiles are smooth, without a break. However, at approximately $t=0.5$ s, a break appears, progressing with time toward the sample edge. The break, marked in the figure by an arrow, separates between the transient state near the edge and the thermodynamic quasiordered phase in the sample interior.[2] The origin of the transient vortex state has been identified by Paltiel *et al.*[1] as surface contamination: By abruptly increasing the field, vortices injected through inhomogeneous surface barriers generate a transient disordered state with a characteristic lifetime $\tau(B)$. This break moves with time manifesting a front-like propagation of the thermodynamic vortex phase.[2] Identification of a transient vortex state at the location x_0 is accomplished by observing the direction of movement of the break relative to x_0. If the break moves towards x_0, the vortex state at x_0 is a transient state. In contrast, if the motion of the break is away from x_0, then the vortex state at x_0 is a quasiequilibrium state. It should also be noted that profiles without a break that precede profiles with a break signify a transient disordered state in the entire sample.

Using the above recipe for the identification of transient disordered vortex states, we identify the range of j and B for which the vortex state at $x_0=-514$ μm is transient (gray area in Fig. 1). Note that the transient states zone occupies the area around the DSMP. This zone narrows down with time, as transient states decay. However, Fig. 1 shows that even after relatively long time, transient vortex states still govern the DSMP. The most intriguing observation in Fig. 1 is that the left boarder of the transient vortex state zone is marked by the onset of the DSMP. In the region to the left of this zone, the transient disordered state has been annealed and a thermodynamic quasi-ordered phase has been established. In the region to the right of this zone, a thermodynamic disordered vortex phase has been established.

The DSMP was measured at several temperatures in the range 20–25 K and j vs B plots, similar to that of Fig. 1, were derived. We find that the effect of temperature on the annealing process is quite dramatic. In particular, at higher temperatures, the width of the transient states zone shrinks faster, e.g., from 220 to 40 G after 3 s at 24 K (compared to from 210 to 70 G after 29 s at 21 K, as can be seen in Fig. 1). Also at $T=24$ K an onset of a DSMP is observed already at 0.04 s, indicating that transient states at lower inductions have already been annealed.

From the instantaneous magnetization curves described in Fig. 1, one can directly measure the lifetime τ of the transient vortex states as a function of the local induction B. By definition, τ is the time elapsed between the onset of the external field and the moment when the transient state at x_0 disappears. We argue that the time corresponding to each instantaneous curve is the annealing time of the initial transient vortex state generated at the induction B_{on}, corresponding to the DSMP onset. This is because for inductions smaller than B_{on} the vortices are already in a quasiordered phase, and for inductions just above B_{on} the vortices are still in a transient disordered state. Figure 3 shows τ as a function of B measured in this way for $T=21$ and 24 K. Evidently, τ increases monotonically with the induction and exhibits a sharp increase as the thermodynamic order-disorder transition field, B_{od}, is approached. Clearly, the lifetime of the transient disordered state should diverge in close vicinity of B_{od}, since the disordered state is thermodynamically favored just above B_{od}. Thus, in normal experimental time windows, transient vortex states always govern the magnetic behavior in the vicinity of B_{od}. This is evident from Fig. 1, which shows that although the gray area narrows down with time, it still extends over a significant induction region even at 29 s. Global magnetic measurements, performed on the same sample in a commercial superconducting quantum interference device, showed that the onset of the fishtail continues to shift up even after 1 h. Fig. 3 shows that as temperature decreases, the annealing time increases, giving rise to a broader lifetime spectrum of the transient states.

The inset of Fig. 3 shows measurements of $\tau(B)$ at different locations across the sample. The observed small variations can be attributed to variations of the electric field across the sample. For positions closer to the sample center the gradient of the electric field increases, giving rise to accelerated relaxation rates, and thus to shorter lifetime of the transient state.

The above results clarify several issues associated with the magnetic manifestation of the solid-solid vortex phase transition. For example, the DSMP in BSCCO cannot be observed below ~ 16 K.[9,11] As a result, the apparently measured vortex order-disorder transition line terminates at low temperatures.[7] This termination poses a long-standing puzzle in the field. The results described above suggest that this apparent termination of the transition line results from broadening of the $\tau(B)$ curve to an extent that in the time period of the measurement, the transient state persists even at the lowest inductions, obscuring a transition from low to high j thus preventing the emergence of DSMP.[8,9,11,17] Note, however, that according to our results, the DSMP will appear even at low temperatures if the time period of the measurement is long enough for the transient states to anneal out. Indeed, several previous measurements[8,9] demonstrated the appearance of DSMP at low temperatures after long waiting times. The recent work of Li and Wen[9] is of particular interest here. These authors used *global* magnetic measurements in BSCCO to demonstrate the appearance of a DSMP at long times and associated it to the relaxation of the metastable profile of the interior magnetic field, which is far from equilibrium state. Our MO results support their results and yield a full physical scenario of the effect, associating it with the increase of the lifetime of transient disordered vortex states at low temperatures. Obviously, $\tau(B)$ also causes distortion of the first order nature of the vortex solid-solid transition in magnetic measurements, as it causes smearing of the DSMP. The smearing effect can be partially eliminated by long-time measurements, or by increasing the temperature. It is expected that $\tau(B)$ is different for different materials and even for different samples of the same material, as it depends on the impurity level of the sample. Impurities, serving as pinning centers, generate metastable states with long lifetime. Thus, broad lifetime spectrum of the transient vortex states is expected in samples with high level of impurity, and, as a result, in such samples, the DSMP is smeared and its onset is shifted to lower inductions. This explains variations of the measured vortex solid-solid transition lines in different samples of the same material; in fact, what one normally measures is a nonequilibrium transition to transient disordered states. Such a transition is strongly affected by the lifetime spectrum of the transient states, which varies appreciably from sample to sample.

In conclusion, our data clearly show that the magnetic behavior of BSCCO around the DSMP is governed by transient vortex states with spectrum of lifetimes $\tau(B)$. These transient vortex states obscure the thermodynamic order-disorder phase transition. Moreover, in normal experimental time windows one always measures a nonequilibrium transition to a transient disordered state with transition that shifts to higher inductions with time, approaching the thermodynamic B_{od}. For a given sample, the behavior of $\tau(B)$ is affected strongly by temperature. As temperature is lowered, the lifetime spectrum $\tau(B)$ broadens causing smearing of the DSMP until it disappears altogether. This gives the wrong impression of an ending point to the transition line. As time elapses, transient states relax and a DSMP emerges even at low temperatures. At high temperatures, $\tau(B)$ approaches a step-like behavior and the transition is, therefore, expected to be definitive and sharp, as indeed borne out in the experiment as a melting transition.[18] Variations of the measured vortex solid-solid transition lines in different samples of the same material may be attributed to different $\tau(B)$ in samples with different level of impurity.

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