Revealing the vortex order-disorder phase transition in small $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals

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The apparent absence of a vortex order-disorder phase transition in small $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals is attributed to fast decay of bulk currents at relatively high temperatures, or to slow annealing of transient disordered vortex states at low temperatures, both obscuring the second magnetization peak that signifies the transition. Experimental procedures for compensating for these effects, leading to the emergence of a second magnetization peak in small samples, are demonstrated. Our results question previous reports on a size effect in the vortex matter phase transition.

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Recent studies have indicated that the quasiordered vortex lattice in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) crystals collapses into a disordered phase through a thermal- and/or a disorder-driven first order transition.[1–4] This order-disorder vortex phase transition is manifested by a reversible magnetization step above the irreversibility line,[5] or by a second magnetization peak (SMP) below it.[6,7] Apparently, the order-disorder vortex phase transition should occur along a continuous line in the *B*-*T* phase diagram.[8–10] However, some experimental studies in BSCCO have indicated the existence of a wide temperature range below the irreversibility line, where the SMP is absent.[11–15] This creates an apparent gap in the transition line between the lowest melting temperature $T_m \cong 40$ K and a temperature $T_h < T_m$ above which the SMP disappears, as schematically shown in Fig. 1. The SMP also disappears in the low temperature range,[6,16–20] resulting in a termination of the measured transition line at T_ℓ, typically 17–20 K, see Fig. 1.

The temperature range $T_m - T_h$ in which the SMP is absent, increases as the sample size decreases, a phenomenon that was interpreted by Wang *et al.*[11,12] as indicating a size effect in the vortex matter phase transition. This interpretation has been disputed by Kopelevich *et al.*[13,14,21] arguing that the absence of SMP in small samples indicates that the origin of the SMP is rather a thermomagnetic instability. In this paper we show that the disappearance of the SMP in small BSCCO crystals can be attributed to either fast decay of bulk currents above T_h or slow annealing of transient disordered vortex states below T_ℓ. We show that each of these effects is more pronounced in smaller samples. Furthermore, we show that by reducing the measurement time window, the SMP in small samples reappears, shifting T_h to higher temperatures. Also, increasing the measurement time window to allow for the annealing of transient vortex states, leads to the emergence of the SMP below T_ℓ. Our results question previous interpretations[11–14,21] given to the absence of the SMP in small BSCCO samples.

Measurements were performed on a number of $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples cut from an optimally doped single crystal (T_c=92 K) grown by the traveling solvent floating zone method.[22] Here we show results for two samples, denoted as S_D and S_d, with dimensions $1.55 \times 1.25 \times 0.05$ and $1.55 \times 0.20 \times 0.05$ mm^3, respectively. A magneto-optical system was employed to image the distribution of magnetic induction across the samples while the external field, H_{ext}, was swept at a constant rate (between 4 and 1600 G/s) from zero up to about 850 G (well above the order-disorder transition field B_{od}=400–500 G). Snapshots of the distribution of magnetic induction were taken successively, using iron-garnet indicators with in-plane anisotropy[23] and a charge-coupled device (CCD) video camera. For sweep rates smaller than 300 G/s snapshots were taken at a constant field intervals of 10 G. For faster rates, snapshots were taken every 36 ms. Local magnetization curves, $m = B(x) - B_{edge}$ vs $B(x)$, were extracted from the induction images. In the figures below we show m at $x/D = x/d = 0.7$ for the large and small samples, respectively, except where noted.

Figure 2 shows local magnetization curves measured in sample S_d at different temperatures, sweeping the external field at a rate of 4 G/s. As the temperature increases from 21 to 27 K, we observe a continuous decrease in the SMP height, defined as the increase in local magnetization from

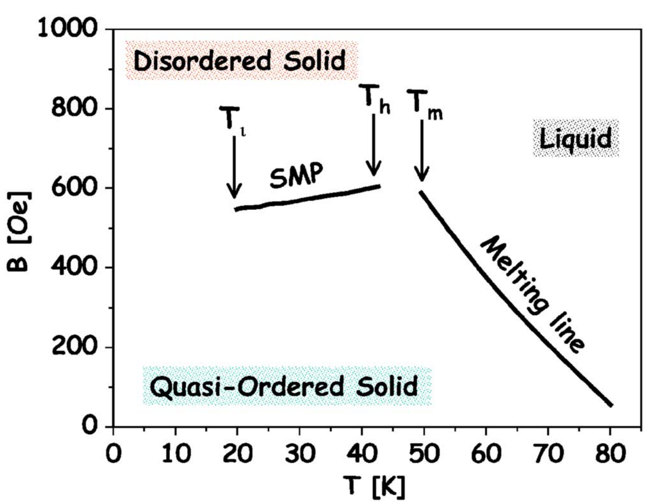

FIG. 1. (Color online) Schematic description of the vortex phase diagram in BSCCO, illustrating the gap and termination point in the order-disorder phase transition line.

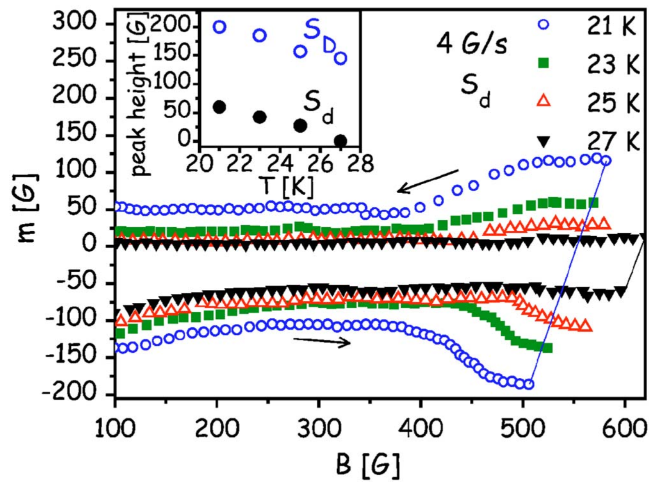

FIG. 2. (Color online) Local magnetization curves, $m=B(x)-B_{\mathrm{edge}}$ vs. $B(x)$, measured in sample S_d at the indicated temperatures, with field sweep rate of 4 G/s. Inset: Peak height as a function of temperature for samples S_d and S_D (bold and open circles, respectively).

the onset to the peak. Note, that this definition eliminates the contribution of surface currents to the local magnetization. The peak height is plotted vs temperature in the inset to Fig. 2 for the small (closed circles) and large (open circles) samples. The peak height decreases gradually with temperature, totally disappearing above 27 K and ~40 K for the small and large samples, respectively.[24] As the melting transition in similar BSCCO samples is observed above ~40 K,[5,6] independent of sample size,[11,12] these results apparently demonstrate a larger temperature gap, T_m-T_h, in the measured transition line for the smaller sample.

We now show that by changing the measurement protocol one can significantly reduce this gap. Figure 3 shows magnetization curves measured in the small sample at 27 K with

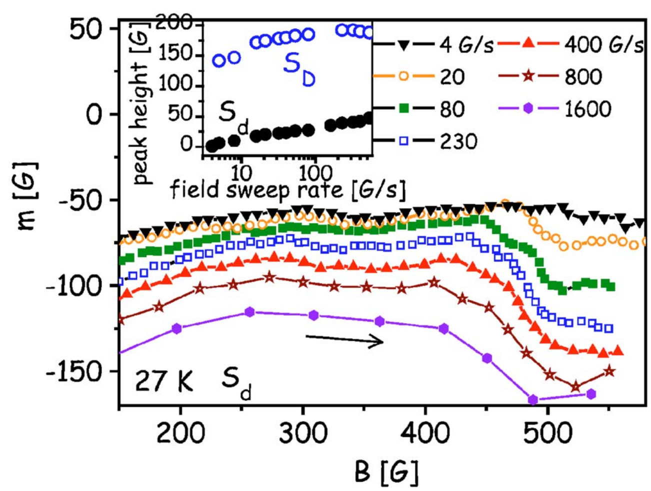

FIG. 3. (Color online) Ascending branch of local magnetization curves measured in sample S_d at 27 K with field sweep rates ranging from 4 up to 1600 G/s. Inset: Dependence of the peak height on the field sweep rate for samples S_d (bold circles) and S_D (open circles).

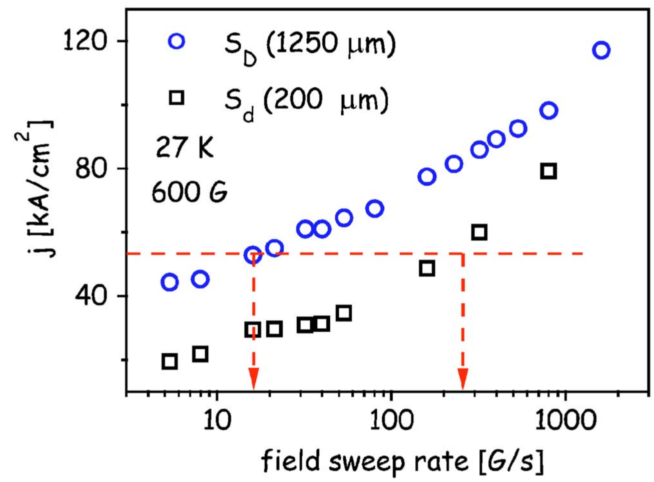

FIG. 4. (Color online) Field sweep rate dependence of the bulk current density at ~600 G in samples S_d (squares) and S_D (circles).

field sweep rates ranging from 4 up to 1600 G/s. It is clearly demonstrated that the SMP builds up as the sweep rate increases. The inset to Fig. 3 shows the dependence of the peak height on the field sweep rate for the small (closed circles) and large (open circles) samples. The increase of the peak height with the sweep rate, observed for both samples, is a direct result of the increase in the bulk current due to the shorter time window of the experiment as the sweep rate increases. This indicates that the disappearance of the SMP at high temperatures is related to relaxation of bulk currents due to flux creep and does not necessarily indicate an absence of the phase transition, as previously proposed;[11–14,21] faster sweep rates compensates for this effect, causing reappearance of the SMP.

In the following we show that the effect of relaxation is more pronounced in smaller samples, suppressing the bulk currents to lower values. We first employ our experimental data to demonstrate that for the same field sweep rate the bulk current is always lower for the smaller sample. Figure 4 shows the field sweep rate dependence of the bulk current density, j, in the two samples, as obtained by fitting the induction profiles around 600 G (above the SMP) to the Biot-Savart law, using a single bulk current (i.e., j is independent of the location across the sample). The figure demonstrates that the bulk current density is always larger in the larger sample.[25] Consequently, for identical measurement protocol, the SMP of the small sample disappears in the background before that of the large sample. Experimentally, it is possible to compensate for the bulk current reduction in the smaller sample by increasing the sweep rate. For example, in order to obtain 54 kA/cm^2 in both samples, one requires sweep rates of 16 and 230 G/s in the large and small samples, respectively, as demonstrated by the dotted lines in Fig. 4.

The reduced bulk current in the smaller sample is a consequence of different current relaxation rates for the two samples. Intuitively, relaxation of j by a certain amount requires the entry of more fluxons in the larger sample and, consequently, longer time. This phenomenon is mathematically expressed by different scaling of the time in samples of different size; the scaling time t_0 increases with the sample

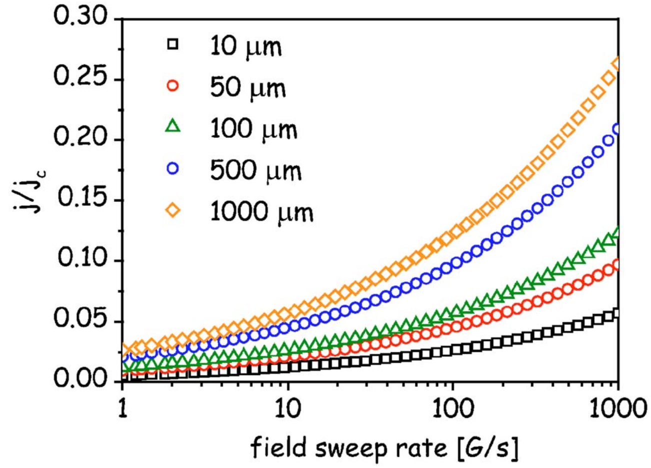

FIG. 5. (Color online) Calculated bulk currents, $j=dB/dx$, normalized to j_c, for the indicated sample widths, calculated for $H_{ext}=1000$ G, $n=3$, and $j_c=10^6$ A/cm^2.

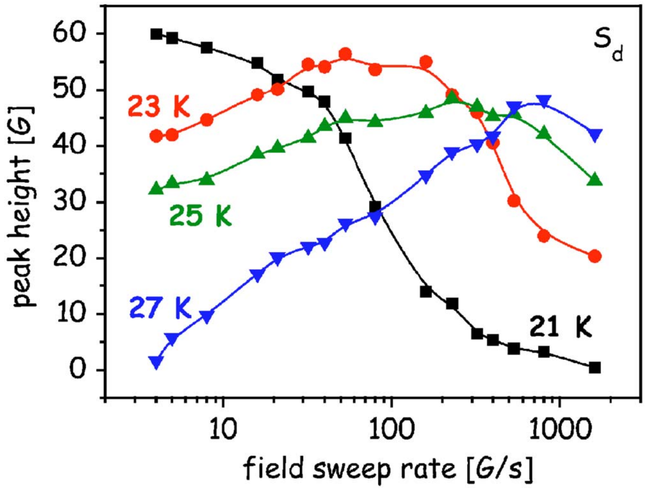

FIG. 7. (Color online) Peak height as a function of field sweep rate at the indicated temperatures, in sample S_d.

width d. For example, as shown in Ref. 26, for a constant magnetic field applied to a slab in the parallel geometry, t_0 is proportional to d^2. In the logarithmic approximation,[26] the activation energy for creep is $U=k_BT\ln(t/t_0)$. Assuming a logarithmic dependence of U on the bulk current j,[27] $U=U_0\ln(j_c/j)$, where j_c is the critical current. Thus one obtains: $j=j_c(t_0/t)^{1/n}$, where $n=U_0/k_BT$. Clearly, this expression applies for $t>t_0$ while for $t<t_0$ $j=j_c$.[28] Since the scaling time t_0 is larger for the larger sample, the bulk current at a given time is always larger in the larger sample.

The above arguments should be modified for our experimental procedure, in which the external field is not constant, but ramped at a constant rate. In order to estimate the size dependence of the bulk current in this case, we solve the diffusion equation[26] for a parallel geometry,[29] $\partial B/\partial t=-\partial E/\partial x$, assuming $B=0$ at $t=0$, and $B=H_{ext}=(dH_{ext}/dt)t$ on the sample edge ($x=\pm d$). We further assume that the bulk current $j=-(c/4\pi)\partial B/\partial x$ is related to the electric field $E(j)\propto(j/j_c)^n$. Figure 5 illustrates the numerically calculated j/j_c vs the field sweep rate for different sample sizes and $H_{ext}=1000$ G, $n=3$, and $j_c=10^6$ A/cm^2, demonstrating that the bulk current increases with the field sweep rate[30–32] and that j increases with the sample size. These results are qualitatively similar to our experimental results presented in Fig. 4. For a quantitative comparison one should use equations corresponding to the perpendicular geometry of a thin sample.

We thus conclude that the apparent gap in the measured transition line above T_h is due to suppression of the SMP resulting from the decay of bulk currents. In small samples this suppression occurs at lower temperatures due to faster relaxation of the bulk currents. In comparing samples of different size, one should compensate for the reduction in the bulk current in the smaller samples. This can be done by adjusting the field sweep rate as was shown above.

We now turn our attention to the termination of the transition line in the low temperature range, below T_ℓ.[6,16–20] The physics behind the disappearance of the SMP in this temperature range is entirely different from that discussed above. This is demonstrated in Fig. 6 showing magnetization

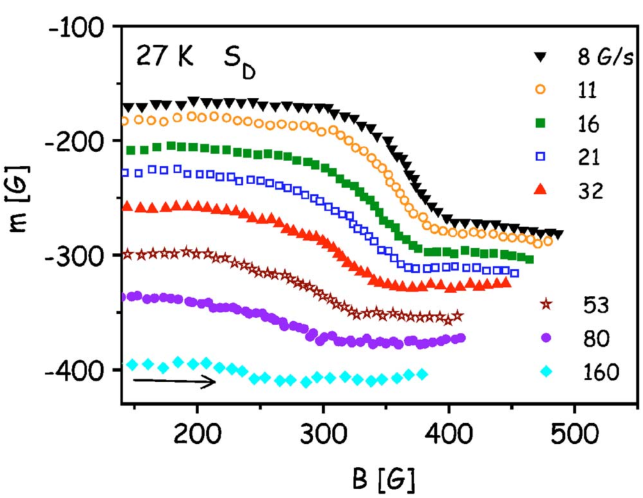

FIG. 6. (Color online) Ascending branches of local magnetization curves measured in sample S_D for $x=200$ μm at 21 K, for the indicated field sweep rates.

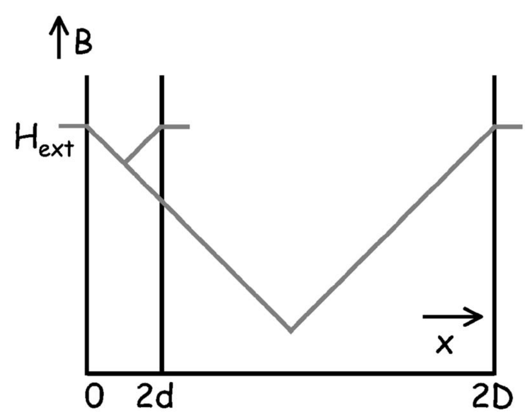

FIG. 8. Schematic illustration of induction profiles generated in samples of different size by the same external field. Note that the average induction in the smaller sample is larger.

curves, measured at $T=21$ K, in sample S_D at $x=200$ μm, for different field sweep rates. In sharp contrast to the 27 K data shown in Fig. 3, here the peak height *decreases* with the field sweep rate. We attribute this phenomenon to transient disordered vortex states that exist below the order–disorder vortex transition induction, B_{od}.[18–20,30,32–35] These transient states are injected to the sample through inhomogeneous surface barriers while the external field increases[36,37] or by "supercooling" of the disordered state while the field decreases.[8,38] These transient states are characterized by their lifetime, $\tau(B,T)$, which diverges as B_{od} is approached and strongly increases as temperature is reduced.[17–20] At low temperatures and high sweep rates (i.e., short time scales), annealing of transient disordered states is hindered; the transient disordered state at low inductions is indistinguishable from the thermodynamic disordered state at high inductions, causing smearing of the SMP. As the sweep rate decreases, the transient disordered states partially anneal and the SMP is exposed, as demonstrated in Fig. 6.

Figure 7 summarizes the effect of sweep rate on the peak height at different temperatures. While at 27 K the peak height essentially increases with the sweep rate, at 21 K it exhibits a sharp decrease. As explained above, the increase of the peak height with the sweep rate at 27 K is a result of decreasing the time window of the experiment, giving rise to larger bulk currents. Effects of transient states at this temperature will be significant only at very high field sweep rates, i.e., time windows shorter than the lifetime of these transient states, as demonstrated by the slight decrease of the peak height observed for 27 K (see Fig. 7 and inset to Fig. 3). As temperature is lowered, the lifetime of the transient states increases[18–20] and thus effects of transient disordered states are pronounced at lower sweep rates. At 21 K, the effect of long living transient states dominates the behavior of the peak height, resulting in a sharp decrease of the peak height for relatively low field sweep rates. At intermediate temperatures (23 and 25 K) one can observe effects of both relaxation and transient vortex states. The crossover between these two competing effects results in a maximum in the peak height at intermediate sweep rates.

Effects of metastable vortex states on the SMP are more severe in smaller samples, because for a given external field the average induction in the smaller sample is larger, as shown schematically in Fig. 8. As the lifetime of transient states increases with the induction,[18–20] on the average transient states with larger lifetimes are involved in the smaller sample. Thus, as the temperature is lowered, the smearing of the SMP is more pronounced in smaller samples. Consequently, in order to observe the SMP in small samples in the low temperature range, one should *decrease*, rather than increase, the sweep rate, to allow enough time for the transient states to anneal out.

The above results question previous interpretations[11–14,21] given to the absence of the SMP in small BSCCO samples. Wang *et al.*[11,12] interpreted it as indicating a size effect in the vortex matter phase transition. However, their measurements were conducted with the same external field sweep rate for all sample sizes. Thus, the observed disappearance of the SMP in those experiments can just be a result of enhanced relaxation in smaller samples, near T_h. In comparing samples of different size one should adjust the field sweep rate in order to compensate for this effect.

Kopelevich *et al.*[13,14,21] reported on the absence of the SMP in small samples as a support to their thermomagnetic instability model for the SMP phenomenon. They also showed, for larger samples, a decrease of the peak height with the sweep rate. Based on our results, the absence of the SMP in small samples is due to enhanced relaxation of the bulk current, and the decrease of the peak height with the sweep rate is due to involvement of transient states with longer lifetime.

In conclusion, we pointed out two different mechanisms for the disappearance of the SMP: fast decay of bulk currents and slow annealing of metastable disordered vortex states at low temperatures. These two mechanisms cause apparent gap in the measured disorder-induced phase transition line above T_h and termination of this line below T_ℓ. The sample size plays an important role, since the current relaxation rate and the relative contribution of transient states to the total magnetization are larger in smaller samples. As a result, the measured low and high termination points, T_ℓ and T_h, in smaller samples occur at higher and lower temperatures, respectively. Increasing the field sweep rate at high temperatures, and decreasing it at low temperatures, can compensate for these effects.

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