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Effects of sample size on the second magnetization peak in $Bi_2Sr_2CaCuO_{8+\delta}$ at low temperatures

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Abstract. Effects of sample size on the second magnetization peak (SMP) in $Bi_2Sr_2CaCuO_{8+\delta}$ crystals are observed at low temperatures, above the temperature where the SMP totally disappears. In particular, the onset of the SMP shifts to lower fields as the sample size decreases – a result that could be interpreted as a size effect in the order–disorder vortex matter phase transition. However, local magnetic measurements trace this effect to metastable disordered vortex states, revealing the same order–disorder transition induction in samples of different size.

Keywords. BSCCO; vortex matter; phase transition.

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The vortex order–disorder phase transition in $Bi_2Sr_2CaCuO_{8+\delta}$ (BSCCO) crystals occurs through a thermal- and/or a disorder-driven first-order transition [1–4]. This transition is manifested by a reversible magnetization step above the irreversibility line [5], or by a second magnetization peak (SMP) below it [6,7]. Recent studies have shown that the order–disorder vortex phase transition should occur along a continuous line in the B–T phase diagram [8–10]. However, several experimental studies in BSCCO have indicated two temperature regions – shown schematically in figure 1 – in which the SMP is absent [11–14]. The first region forms a gap in the measured transition line between the lowest melting temperature, $T_{\mathrm{m}} \simeq 40$ K, and a temperature $T_{\mathrm{h}} < T_{\mathrm{m}}$. In our previous publications [15,16], the disappearance of the SMP in this temperature region has been attributed to the decay of bulk currents. The increase in the temperature range of the gap, $T_{\mathrm{m}} - T_{\mathrm{h}}$, with decreasing sample size [11–14,16–18] was attributed to faster decay of bulk currents in smaller samples.

The SMP also disappears in the low temperature range [6,15,19–23], resulting in a termination of the measured transition line at T_{l}, typically 17–20 K (see figure 1). The obscuring and eventual disappearance of the SMP with decreasing temperatures has been ascribed to the presence of long living metastable disordered vortex states [8,19–25]. Until now there have not been reports on the sample size dependence of this phenomenon. In this paper, we demonstrate the effects of sample size

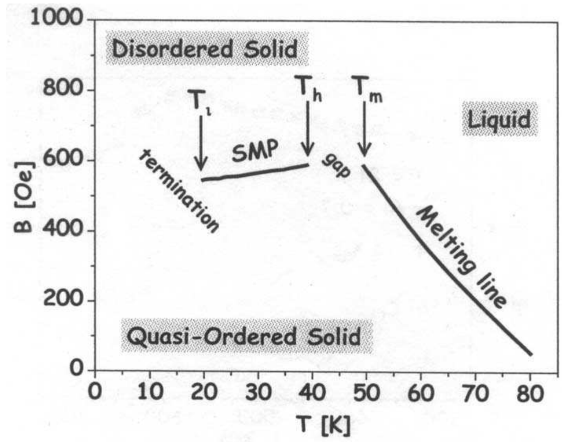

Figure 1. Schematic description of the vortex phase diagram in BSCCO, illustrating the gap and the termination point in the order–disorder phase transition line.

on the SMP in the low temperature range, above the termination temperature, T_{l}. These effects could be interpreted as implying a size effect in the vortex matter phase transition. However, we show that the observed effects are rather associated with different distributions of lifetimes of metastable disordered vortex states in samples of different size. Determination of the order–disorder transition induction, avoiding effects of metastable states, yields the same transition induction, independent of the sample size.

Measurements were performed on several $Bi_2Sr_2CaCuO_{8+\delta}$ samples cut from an optimally doped single crystal ($T_{\mathrm{c}} = 92$ K) grown by the traveling solvent floating zone method [26]. 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. The samples were zero-field-cooled to the measurement temperature where 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, magneto-optical 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 magneto-optical indicator with in-plane anisotropy [27] and a high-speed charge-coupled device (CCD) camera.

Figure 2 presents results of relaxation measurements conducted after application of various external fields at 24 K. Instantaneous magnetization curves for both samples were generated by connecting all points measured 3.4 s after the application of the external field. The bulk current $j \propto \mathrm{d}B/\mathrm{d}x$ was extracted at $x = 0.7d$ for both samples and plotted vs. H. Both curves show a clear transition from a low value of $\mathrm{d}B/\mathrm{d}x$ (low bulk current) to a higher value at higher applied fields [28]. This jump from a low to a high bulk current relates to the SMP. Note that the SMP is observed around 610 G in the larger sample, and around 450 G in the smaller sample. Since the SMP usually signifies the order–disorder vortex phase transition, its shift to lower fields (by ~160 G) in the smaller sample apparently implies a lower transition field for the smaller sample.

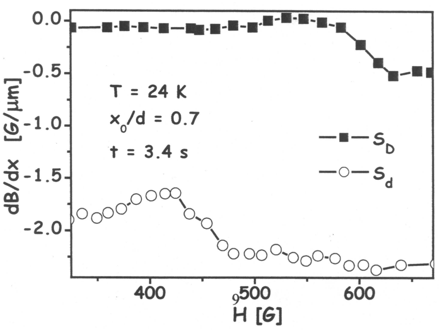

Figure 2. Instantaneous local magnetization curves, $\mathrm{d}B/\mathrm{d}x$ vs. H, measured at 24 K in samples S_d and S_D (open and bold symbols, respectively).

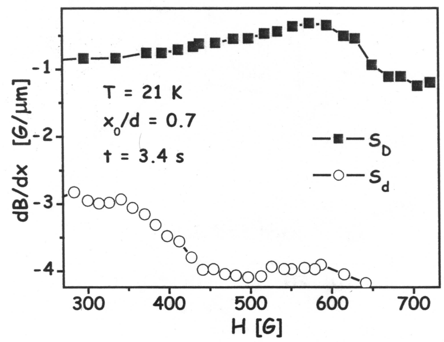

Figure 3. Instantaneous local magnetization curves, $\mathrm{d}B/\mathrm{d}x$ vs. H, measured at 21 K in samples S_d and S_D (open and bold symbols, respectively).

As the temperature decreases to 21 K (see figure 3), the SMP is found around 600 G and 380 G in samples S_D and S_d, respectively, i.e. the shift in the SMP position between the two samples increases to 220 G. A further decrease of the temperature is expected to shift the SMP in both samples to even lower fields, until at low enough temperature the SMP will totally disappear [20]. Obviously, this disappearance will occur first in the smaller sample. Such results, demonstrating the absence of SMP in small samples, could be interpreted as a size effect in the vortex matter phase transition. However, as we explain below, this is not the case. We will show that for a given external field, differences between the magnetic behaviors of samples of different size result from different distribution of metastable disordered vortex states with different lifetimes.

Figure 4 shows instantaneous magnetization curves, $\mathrm{d}B/\mathrm{d}x$ vs. B, measured in both samples at 21 K, 3.4 s after application of each external field. The figure demonstrates that the same measurements as described in figure 3, when plotted vs. the local induction B, present no effect of the sample size on the SMP: the SMP is observed around 320 G for both samples. Magnetization curves plotted for different times also yield the same SMP induction for both samples, as demonstrated for 29 s by the bold and open triangles in figure 4. Also, the SMP fields remain unaffected by the sample size when the temperature is changed. We therefore conclude that the observed effects of sample size disappear when measurements are compared for the same local induction B.

In recent years, several works have shown that magnetic measurements near the order–disorder phase transition are strongly affected by the presence of metastable disordered vortex states [8,19–25]. These metastable states are generated by either injection of vortices through inhomogeneous surface barriers [29,30] or by supercooling of the disordered vortex phase [8]. The metastable disordered states are characterized by their lifetime, τ, which is a function of induction and temperature [20–23]; τ increases with the induction, diverging towards the induction transition B_{od}, and decreases with increasing temperature. Enhanced involvement of metastable disordered states is observed in fast measurements (e.g. by increasing

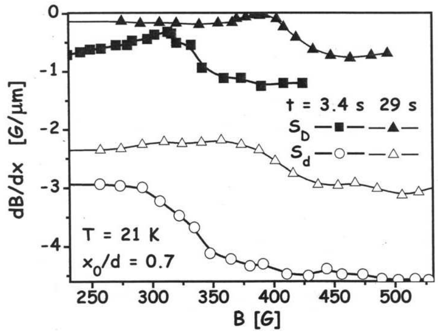

Figure 4. Instantaneous local magnetization curves, $\mathrm{d}B/\mathrm{d}x$ vs. B, measured at 21 K in samples S_d and S_D (open and bold symbols, respectively), for $t = 3.4$ (squares and circles) and 29 s (triangles) after field application.

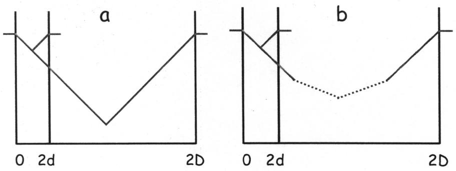

Figure 5. Schematic illustration of induction profiles generated in samples of different sizes, immediately after the abrupt application of the same external field (**a**), and also after a time elapse, when metastable disordered vortex states begin to anneal (**b**).

the field sweep rates) as metastable states with shorter lifetimes play a role in the time window of the experiment [20–24].

We now explain the size dependence of the SMP field shown in figures 2 and 3. Immediately after an abrupt application of a certain external field, vortices in the entire sample are in a metastable disordered state. As plotted schematically in figure 5a, the induction profile generated after the application of the field is 'deeper' in the larger sample. Therefore, metastable disordered states with much shorter lifetimes are involved in measurements of the larger sample. Over time, the metastable disordered states anneal, starting from the lowest induction (at the center of the sample). Figure 5b describes the situation at a certain time after the application of the field: metastable disordered vortex states annealed at the center of the large sample while the vortex state in the small sample is still entirely disordered. Thus, measurements near the center of the samples yield low bulk current for the large sample and high current for the smaller one. As a result, the applied field in this case is smaller than the SMP field for the large sample and larger from the SMP field for the small sample. It thus appears that the SMP field of the large sample is higher than the SMP field of the small sample. This example shows that effects of metastable disordered states are more pronounced in measurements of smaller samples because for a given time and external field the relative portion of metastable disordered states is larger in smaller samples.

As the temperature is lowered, the lifetime of the metastable states increases [20–23] and thus they affect the measurements even at lower fields. As a result, the SMP shifts to lower fields with decreasing temperature, until it disappears at a low enough temperature [20]. Since the SMP field is always lower for smaller samples, the disappearance will occur first in the smaller sample, implying higher T_l for smaller samples. This increase in T_l should be interpreted merely as an effect of metastable disordered states and not as a size effect in the vortex matter phase transition. Such measurements in the low temperature region should be performed over a long time period in order to enable annealing of metastable disordered states.

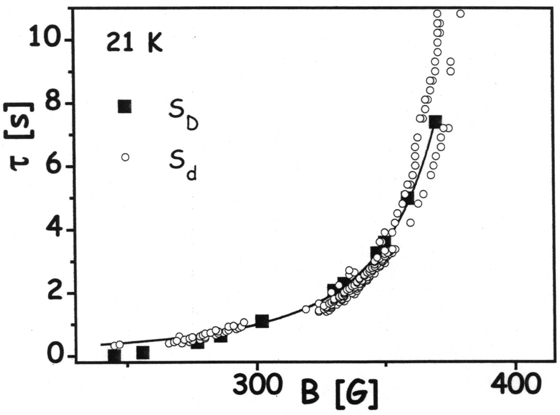

Figure 6. Lifetime of disordered vortex states, $\tau(B)$, measured at 21 K for samples S_d and S_D (open and bold symbols, respectively).

Alternatively, effects of metastable vortex states can be bypassed by analyzing the data in a way discussed in ref. [22].

As mentioned above, the magnetic measurements plotted in figure 4 as a function of B show no difference between the SMP of the samples. However, we note that metastable disordered states still affect these measurements. Figure 4 demonstrates the effect of metastable disordered states, causing a shift of the SMP to higher fields with time [21,24,31]. In order to determine the thermodynamic induction transition, $B_{\rm od}$, avoiding effects of metastable disordered states, one should measure the lifetime of the metastable disordered states as a function of T and B (our method for extracting τ from relaxation measurements can be found in refs [20–23]). Figure 6 presents $\tau(B)$ measured at 21 K for both samples, demonstrating similar curves for both samples.

The lifetime of the metastable disordered states, plotted in figure 6, can be used for determination of the thermodynamic transition induction, $B_{\rm od}$ by extrapolating τ to infinity (for details see refs [20–23]). This procedure yields the same $B_{\rm od}{\sim}400$ G at 21 K for both samples.

In conclusion, we have demonstrated that magnetic measurements of the vortex order–disorder phase transition in BSCCO are affected by the sample size also in the low temperature region where relaxation effects can be neglected. We showed that the SMP field decreases with decreasing sample size – a result that may be misinterpreted as a size effect in the vortex matter phase transition. We demonstrated that this effect of size is associated with the presence of metastable disordered vortex states with B-dependent lifetime. The different induction profiles obtained in samples of different size, for the same applied field, cause this apparent size effect. Measurements as a function of local induction show no size dependence of the SMP. Moreover, measurements of the field dependence of the lifetimes of the metastable states in both samples show similar results, implying the same transition induction, $B_{\rm od}$, independent of the sample size.

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