Effects of sample size on magnetic properties of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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The magnetic moment and relaxation rates in $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals exhibit remarkable dependence on the sample size in the vicinity of the vortex order–disorder phase transition line. Specifically, we find that: (1) the magnitude of the normalized magnetic moment *increases* as the sample size *decreases*, (2) the relaxation rate *increases* with the sample size, and (3) the difference between the relaxation rates in samples of different size, decreases with temperature and field. These phenomena are attributed to dynamic coexistence of quasi-ordered and metastable disordered vortex states in the samples, in the temperature and field range near the vortex phase transition. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1851883]

Effects of the sample size on the irreversible magnetic properties of superconductors are anticipated,[1,2] since the irreversible magnetic moment, ***m***, originates from a *nonuniform* distribution of magnetic flux in the sample interior. Thus, in superconductors, contrary to ferromagnets, the conventional concept of magnetization, ***M***, as magnetic moment per unit volume, does not yield a quantity which can be interpreted as an intrinsic or uniform volume property. In fact, the magnetization of a non-equilibrium superconductor *grows* with sample dimensions. For example, the Bean critical state model for a slab predicts a linear relationship between the magnetization and the thickness d of the slab.[3] Accordingly, scaling of the magnetization curves of samples of different size by the geometrical factor d, is expected to cause all data points in the irreversible regime to collapse into a single curve. Deviations of magnetic data from the predicted linear relationship have been attributed to field dependence of the critical current density.[1]

Time relaxation of the magnetic moment is also affected by the sample size. This is because in the magnetic relaxation process, the time is scaled differently in samples of different size,[4] e.g., for the slab geometry mentioned above, the scaling time t_0 is proportional to d^2. Thus, the initial relaxation of a narrow sample is expected to be faster than that of a wider sample. The above mentioned theoretical predictions, regarding the size dependence of the irreversible magnetization and its relaxation rates, have been confirmed experimentally in temperature and field ranges far away from vortex phase transition lines.[1,5]

The present study focuses on effects of the sample size on the magnetic behavior of $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals near the disorder-induced vortex phase transition.[6] This phase transition is manifested by the appearance of an anomalous second magnetization peak (SMP) in the magnetization curve of the sample. Our measurements show that the magnetic moment and its relaxation rate close to the SMP exhibit unusual dependencies on the sample size. We attribute these results to the presence of metastable disordered vortex states in the samples, in the temperature and field range near the vortex phase transition.

Measurements were performed on two $Bi_2Sr_2CaCuO_{8+\delta}$ samples, denoted as S_D and S_d, of dimensions $2.58\times1.45\times0.02\ mm^3$ and $2.58\times0.69\times0.02\ mm^3$, respectively, cut from the same optimally doped $Bi_2Sr_2CaCuO_{8+\delta}$ single crystal (T_c=92 K).[7] Measurements were performed using a Quantum Design (MPMS-5S) SQUID.

The inset to Fig. 1 shows magnetization loops measured for both samples at 22 K. The magnetization described in this figure is the total magnetic moment m normalized to the sample volume, and as expected from the Bean model, the magnetization in the wider sample, S_D, is larger. The same model predicts an overlap of the magnetization loops after normalizing the measured magnetic moment m by the square of the sample width. However, as shown in Fig. 1, the normalized magnetization loops overlap in most of the field range, except in a small region between the first and the second magnetization peaks. In this region, on the ascending branch of the loop, the magnitude of the normalized magnetization is *larger* in the narrow sample S_d. In the descending branch of the loop an opposite phenomenon is observed: the magnitude of the normalized magnetization is smaller in the narrow sample. Previous works have demonstrated the presence of metastable disordered vortex states in the field range below the SMP where the normalized magnetization curves deviate.[8,9]

Figure 2 summarizes measurements of the normalized relaxation rate $(1/m)(dm/dlnt)$ in samples S_D and S_d as a

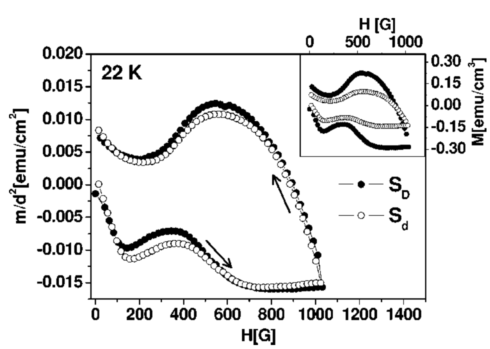

FIG. 1. Magnetization loops measured for S_D (full) and S_d (open symbols) at 22 K, normalized to the square of the sample width. Inset: Magnetization loops for the two samples.

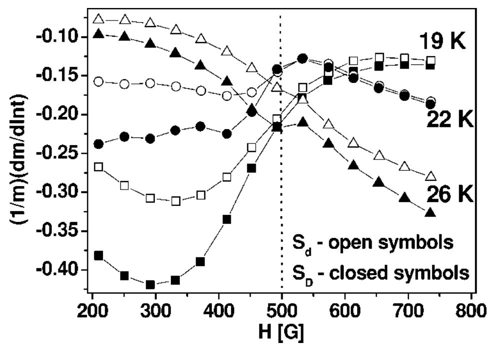

FIG. 2. Normalized relaxation rate in samples S_D (full) and S_d (open symbols) as a function of field, for the indicated temperatures. The dashed line indicates the approximate location of the transition field.

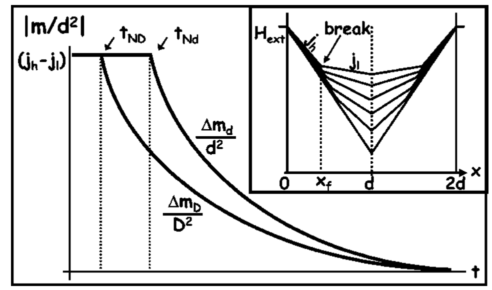

FIG. 3. Schematic description of the contribution of the metastable disordered vortex states to the magnetic moments of the large (S_D) and small (S_d) samples, as a function of time. The nucleation times of the thermodynamic quasi-ordered states are t_{ND} and t_{Nd}, for the large and small samples, respectively. Inset: Schematic description of the time evolution of the induction profile across a sample.

function of field, at three different temperatures. The time dependence of the magnetic moment is approximately logarithmic, thus during the measurement time (60 min), the normalized relaxation rate is approximately constant. This figure reveals several surprising results in the field range below the order–disorder transition field B_{od} (approximately 500 G): (a) the relaxation rate *increases* with decreasing temperature; (b) the relaxation rate is always *higher* in the larger sample independent of temperature; (c) the difference between the relaxation rates of the different samples decreases with increasing temperature and field. For fields larger than the transition field the relaxation rate increases with temperature as normally observed, and the difference between the relaxation rates of the different samples is significantly reduced.

In the following we interpret the experimental data assuming a dynamic coexistence of quasi-ordered and metastable disordered vortex states in the samples. The metastable states anneal at a rate dictated by the annealing time, τ, which depends on the induction B and temperature T: τ decreases with T as thermally activated processes are enhanced, and increases with B diverging to infinity as B_{od} is approached[8,10] since the disordered state is thermodynamically favored just above B_{od}. Application of the same external field generates different induction profiles in samples of different size, and thus metastable states with different lifetimes are involved. Consequently, the relative contribution of the metastable states to the measured magnetic moment, and its relaxation with time, become sample size dependent.

The coexistence of quasi-ordered and metastable disordered vortex states is revealed in magneto-optical imaging of the induction profiles.[11] The inset to Fig. 3 is a schematic description of the time evolution of the induction profile across a sample suddenly exposed to an external magnetic field lower than the transition induction B_{od}. The sudden injection of vortices by the external field creates a disordered vortex states throughout the entire sample. This state is characterized by a relatively high current density j_h. The thermodynamically favored quasi-ordered phase, characterized by a relatively low current density j_l, starts to nucleate at the sample center where the induction is minimal, and propagates towards the sample edges. The interface between the quasi-ordered and disordered states is revealed by a "break" in the induction profile separating between regions of different current density.

Denoting the location of the break by x_f, the magnetic moment of the sample becomes $m=(2d-x_f)x_f j_h+(d-x_f)^2 j_l$. The contribution Δm to the magnetic moment due to the transient disordered states, $\Delta m=m-d^2 j_l=(2d-x_f)(j_h-j_l)x_f$, depends linearly on the sample size d, and it varies with the position x_f of the break in the profile. The normalized contribution

$$\Delta m/d^2=(1-x_f/2d)(x_f/2d)(j_h-j_l) \quad (1)$$

becomes independent of the sample size in two cases: (1) when $x_f=0$, i.e. the transient states are completely annealed and thus $\Delta m=0$. Such a situation occurs at high temperatures, very low fields or long times; (2) when $x_f=d$, i.e., the sample is completely filled with transient disordered vortex states, and $\Delta m=(j_h-j_l)/4$. Such a situation occurs at low temperatures, high fields close enough to B_{od}, or short times. Thus, size effects due to metastable disordered vortex states are expected to be nonmonotonic functions of temperature, field and time, diminishing at extreme values of these variables.

For simplicity, let us compare two samples: a small sample of size d and a large sample of size D, suddenly exposed to the same external field $H_{ext}<B_{od}$. Let us denote by m_d and m_D the total magnetic moment of these samples, respectively. Using Eq. (1), one can easily show that $\Delta m_d/d^2 \geqslant \Delta m_D/D^2$, when the equal sign applies when $x_f=0$ or $x_f=D$. Thus, on the ascending field branch of the magnetization loop, the normalized magnetic moment of the small sample should be always larger than that of the large sample, except for very low or very high fields or temperatures, or very long or short times. On the descending field branch of the loop, supercooled disordered vortex states start to anneal at the sample edge, where the induction is minimal. As a result, the opposite relationship holds, i.e., $\Delta m_d/d^2 \leqslant \Delta m_D/D^2$, in full agreement with the experimental results described in Fig. 1.

Figure 3 schematically describes the contribution of the metastable disordered vortex states to the magnetic moments of the large and small samples, as a function of time. One can distinguish between three time regions defined by the nucleation times t_{ND} and t_{Nd} of the thermodynamic quasi-ordered states in the large and small samples, respectively. Clearly, for the same applied external field, $t_{ND}<t_{Nd}$, be-

cause the nucleation takes place at the sample center where the induction is minimal,[8] and the induction at the center of the larger sample is lower. The contribution of the annealing of metastable states to the measured relaxation rate in both samples diminishes in very short times ($t < t_{ND}$) before the formation of the quasi-ordered phase front, and in very long times after this front has reached the samples edge. In the time interval $t_{ND} < t < t_{Nd}$, annealing of the metastable states contribute to the relaxation only in the large sample. Thus, in this time interval the large sample is expected to exhibit significantly larger relaxation rate. The difference between the relaxation rates of the large and small samples is expected to be a nonmonotonic function of temperature and field, since the annealing process is very fast at high temperature, thus it occurs in much shorter time than the time window of the measurement. Likewise, at a very low temperature the annealing process is extremely slow to be sensed in the measurement time window. Similarly, at very low fields the annealing processes is very fast, and at high fields, close to B_{od}, it becomes extremely slow. In the time range $t < t_{Nd}$, annealing of the metastable vortex states affect the relaxation measured in both samples. Here the small sample is expected to exhibit a higher relaxation rate up to the point where the annealing process is completed.

The above predictions regarding the size dependence of the normalized magnetic moment and its relaxation rates, as a function of time, field and temperature, are qualitatively confirmed in the measurements described in Fig. 2. Quantitative analysis requires measurements of $\tau(B,T)$ in the samples to enable calculations of x_f and dx_f/dt versus time, field, and temperature.

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