

## Dynamic characteristics of the anomalous second peak in the magnetization curves of Bi-Sr-Ca-Cu-O

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We present magnetization curves for Bi-Sr-Ca-Cu-O crystals which exhibit an anomalous second peak. Between 20 and 40 K the peak disappears gradually with time. At lower temperatures (18 K) the peak is absent in the short-time limit and it is gradually built up with time. A smooth universal function relates the magnetization at the peak (400 Oe) with that at the minimum (200 Oe) for all isotherms and at any given time, thus demonstrating the absence of the anomalous peak in the short-time limit at all isotherms.

Numerous recent reports<sup>1-6</sup> describe an anomalous increase in the width of the magnetization loops of high-temperature superconductors (HTS) with the increase of the external magnetic field. Such an anomaly, described as a "peak effect," has already been observed in conventional, low-temperature superconductors.<sup>7</sup> Several explanations have been proposed for this anomaly. Conceptually, these explanations may be divided into "static" and "dynamic" classes according to their (implicit) prediction of the behavior at the shortest time scale,  $t \rightarrow 0$ . The static approach attributes the anomaly to, e.g., oxygen-deficient superconducting areas, which become effective in higher fields due to suppression of the order parameter.<sup>1</sup> In this approach the anomaly may be present even at  $t = 0$ . On the other hand, in the dynamic approach the magnetization curves do not exhibit any anomaly in the short-time scale. The anomaly is a result of slower decay of the magnetization in the field range where the peak is observed.<sup>3-5</sup> The reason for this slower decay may be related to the changes in flux properties.<sup>8,9</sup> The absence of this anomaly in the short-time scale has not yet been demonstrated. In this article we focus on the dynamic properties of the magnetization curves of Bi-Sr-Ca-Cu-O (BSCCO) crystals which exhibit the peak effect and demonstrate the absence of the peak for  $t \rightarrow 0$ .

We have measured three samples—labeled *B1*, *B2*, and *B3*—of nominal composition  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ . Sample *B1*, a  $1800 \times 1800 \times 17 \mu\text{m}^3$  crystal, has a transition temperature  $T_c \approx 88$  K. Sample *B2*, of very similar dimensions and  $T_c \approx 86.5$  K, is taken from another batch. *B3* is cleaved from *B1*; its dimensions are approximately  $1800 \times 700 \times 1 \mu\text{m}^3$ . Details of sample preparation are

described in Ref. 10.

The magnetization was measured in a Quantum Design magnetometer. A scan of 2 cm ensured minimization of the inhomogeneities in the external field. Two kinds of experiment have been done. In the first one we measure the magnetization curve  $M(H)$  at a constant temperature  $T$  and pause at each field  $H$  to detect the magnetic relaxation. In the second, we measure the temperature dependence of the magnetization at a constant field, pausing at each temperature for magnetic relaxation measurements. We refer to these magnetization measurements as  $M_T(H, t)$  and  $M_H(T, t)$ , respectively.

We will now describe the  $M_T(H, t)$  measurements. The sample is zero-field cooled to the measurement temperature and the magnetization loop is recorded in steps of typically 50–100 Oe. We first record the loop in the most rapid mode possible in our technique, spending approximately 80 sec for each data point. We refer to this curve as the "static" curve. We then repeat the loop but now, at each field we record the magnetization as a function of time for 2–4 hours. These curves will be referred to as the "dynamic" curves. The step in the field after the end of each relaxation process produces a magnetization which is within 1–5% of the static curve, with more apparent deviations from this curve as temperature decreases below 26 K. These low-temperature deviations are expected in view of the fact that the step in the field (100 Oe) is becoming smaller than  $H^*$ , the first field for full flux penetration.<sup>11</sup>

Figure 1 presents a typical magnetization curve, at  $T = 26$  K, including several minor loops. The figure exhibits a pronounced anomaly in the width of the magnetization curve around 400 Oe. A similar peak is observed

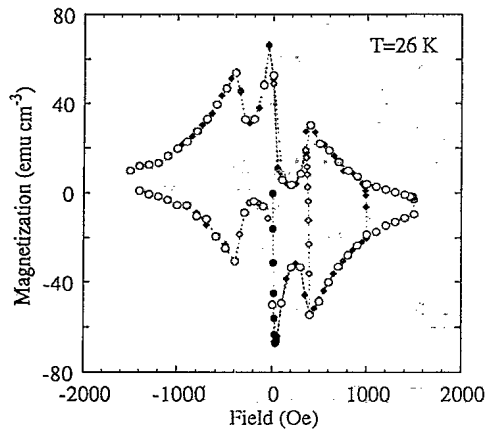


FIG. 1. Magnetization curve for Bi-Sr-Ca-Cu-O (sample B2) at 26 K, including minor loops.

between 20 and 40 K; it is most pronounced at intermediate temperatures and is gradually smeared out for either increasing or decreasing temperatures. It should be noted that the location of the anomaly is temperature independent but it is sample dependent.

In addition to the anomalous width, Fig. 1 exhibits two interesting features which point towards a significant contribution of surface barriers<sup>12</sup> to the shape of the magnetization curve. These are (i) the slope  $dM/dH$  when the field is decreased from its maximum value is similar to the (demagnetization corrected)  $1/4\pi$  Meissner slope,<sup>2</sup> and much larger than the slope predicted by the Bean model.<sup>11</sup> (ii) During the process of field decrease the magnetization  $M$  is approximately zero below the anomalous maximum. This  $M \approx 0$  value is one of the main fingerprints of surface barriers.<sup>13-15</sup> The strong presence of surface barriers leads us to conclude that the magnetization curve of Fig. 1 is a superposition of bulk ( $M_b$ ) and surface ( $M_s$ ) magnetization. The (temperature-dependent) relative strength of each contribution determines the general feature of the curve.

Pronounced relaxation of the magnetization is apparent in all fields and temperatures of these experiments. The relaxation is not logarithmic with time. Moreover, we observe a strong "asymmetry" in the relaxation rate for flux entry (in the process of increasing the field) and flux expulsion (field decreasing) with faster flux entry in most temperature and field range of the anomalous peak, consistent with the predictions of Ref. 15. It is important to note that *this asymmetry prevents any reasonable estimate of the equilibrium magnetization  $M_{eq}$* . The estimation of  $M_{eq}$  is done by averaging the magnetization  $M_+$  and  $M_-$  measured while increasing and decreasing the field, respectively. Applying this procedure here would of course yield a time-dependent  $M_{eq}$ . We are thus forced to analyze the time dependence of the magnetization without any knowledge of the initial or final values. To bypass this problem we analyze the time evolution of the *derivative* of the magnetization with respect to the time. Note that by analyzing the derivative of the raw data we introduce inevitably large scatter of the experimental points, in particular when the absolute value of the measured magnetization is relatively small (e.g., in

the descending branch of the magnetization where  $M \approx 0$ ). Typical data, for 26 K, are presented in Fig. 2.

The nonzero slopes of the data in Fig. 2 demonstrate clearly that the relaxation is not logarithmic in time. The use of the "interpolation formula,"<sup>9</sup> which was successfully applied in other cases,<sup>16</sup> is impractical here because of the scatter in the derivative of the experimental data. Moreover, the *a priori* use of this formula is not justified here because of the presence of surface barriers; these barriers contribute to the magnetic relaxation, a contribution which is not taken into account in the theoretical work of Ref. 9. The linear behavior of the  $dM/d \ln t$  curves in the log-log plot of Fig. 2, at least for the less-scattered data, leads us to choose to fit our data to a power-law  $M \sim t^{-\mu}$  (solid lines in Fig. 2). The derived exponents yield a reasonable qualitative description of the field and temperature dependence of the relaxation rates. The temperature dependence of these exponents is summarized in the inset to Fig. 2 for several representative fields. The most striking feature of this inset is the crossover in the dynamic behavior from low fields (where the relaxation rates slow down with increasing temperature) to high fields (with increasing relaxation rates).

The implication of the crossover in the relaxation rates to the shape of the magnetization curves is presented in Fig. 3 where we describe the time evolution of the magnetization curve at three representative temperatures. The broken and the solid lines in the figures connect the measured points taken at the earliest and at the latest measured times, respectively. A crossover in the time evolution of the peak—from low to high temperatures—is apparent. At low temperatures (18 K) the anomalous peak is absent in the short-time limit and is gradually built up due to the fast relaxation of the low-field magnetization.

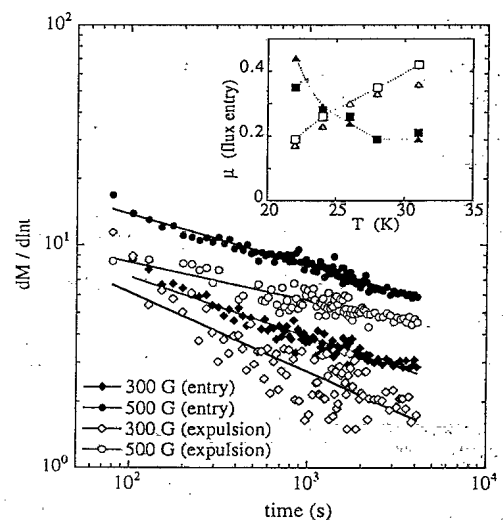


FIG. 2. Typical data for  $dM/d \ln t$  at 26 K and for the indicated fields for sample B2. The solid lines are fits to a power law. Inset: Summary of the temperature dependence of the exponent  $\mu$  in the power law for "low" fields (full triangles and squares represent data for 200 and 300 Oe, respectively) and for "high" fields (open triangles and squares for 500 and 600 Oe, respectively). The dotted lines are guides for the eye.

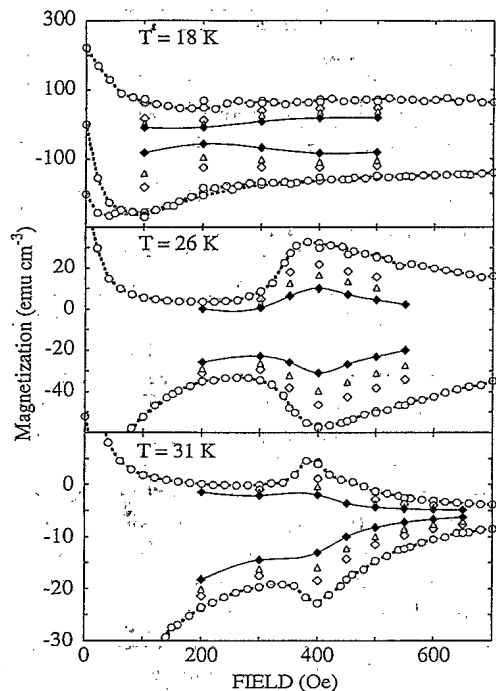


FIG. 3. The time evolution of the magnetization  $M$  at 18, 26, and 31 K. The symbols are representative values of  $M$  at a time  $t$  after the field change:  $t=80$  (circles), 330 (open diamonds), 1000 (triangles), 5500 (full diamonds at 26 and 31 K) and 12000 s (full diamonds for 18 K). The broken lines connect the points for the "static" curve (80 s). The solid lines are the "envelopes" of points taken for the longest time. Data for 26 and 31 K are taken for sample B2 whereas at 18 K it is for sample B3 in order to achieve full penetration already at 100 Oe.

On the other hand, at high temperatures (31 K) the high-field relaxation is faster and the anomalous peak disappears gradually.

Our data demonstrate clearly that the peak is a direct consequence of vortex—dynamic characteristic. The possibility to observe it depends on the time window of the experiment with respect to the characteristic time of the magnetization decay. At low temperatures the dynamics is slow enough to allow for the observation of the "creation" of the anomaly; at intermediate temperatures the peak is already present on our shortest time scale and it is possible to follow its smearing with time. Thus, the experimental time window for which the peak can be observed is shifted gradually towards longer times as temperature is decreased. Such an interplay of time and temperature was first described by Chikumoto *et al.*<sup>5</sup> To further demonstrate this point we turn now to the measurements of  $M_H(T, t)$ .

In these measurements the sample is zero-field cooled to 15 K where a field  $H$  is applied and the magnetization is measured for approximately 6000 s. The sample is then warmed up to 43 K in increments of 2 K, with pausing time of 6000 s at each of the 15 isotherms. We then plot, in Fig. 4, the value of the magnetization at 400 Oe ( $M_{400}$ ) as a function of the magnetization at 200 Oe ( $M_{200}$ ) for all the 15 isotherms. To distinguish between isotherms we use alternately full and open circles, start-

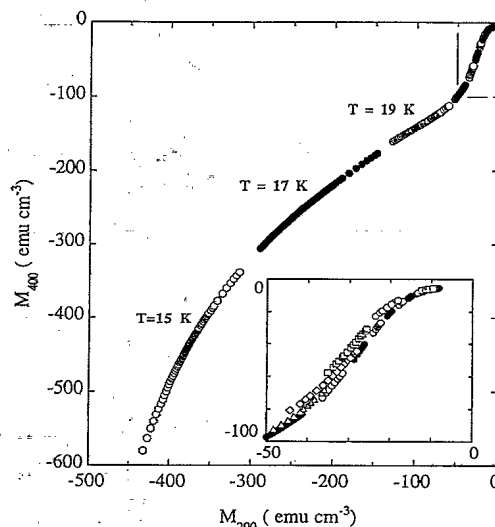


FIG. 4.  $M_{400}$  vs  $M_{200}$  for 15 isotherms of  $M_H(T, t)$  data for sample B2, starting at 15 K at the bottom left of the figure. Inset: Isotherms between 21 and 43 K for  $M_H(T, t)$  (alternating full and open circles) and isotherms between 22 and 40 K from  $M_T(H, t)$  (noncircular symbols). The shortest possible time is at the bottom left of each isotherm.

ing at the 15-K isotherm at the bottom left of the figure. The bottom left of each isotherm starts at the shortest time (80 s). In the inset we focus on isotherms between 21 and 43 K. The most striking feature of this figure is the smooth functional dependence of  $M_{400}$  on  $M_{200}$  for 15 isotherms and total time interval of 90 000 sec. Note that  $M_{200}$  and  $M_{400}$  represent magnetization values which are approximately at the minimum and at the maximum of the anomaly, respectively. Thus, the figure clearly demonstrates that the two variables—temperature and time—rescale each other in the process of relaxation.<sup>17</sup> As temperature decreases, the chosen experimental time window "slides" to effectively shorter and shorter times. Thus, by lowering the temperature we are able to probe shorter time scales and provide evidence that *the  $t=0$  magnetization does not exhibit any measurable anomaly*. At higher temperatures our time window is effectively in the long-time limit and we are able to observe the relaxation of this anomaly.

To complete the discussion concerning the moving-time window we return now to the  $M_T(H, t)$  data and compare values of  $M_{400}$  with  $M_{200}$  derived from these data. We add five representative isotherms (22, 24, 26, 31, and 40 K) to the inset of Fig. 4 (open triangles, diamonds, squares, dotted-circles, and dotted-squares, respectively). These data overlap with that derived from the  $M_H(T, t)$  measurements, demonstrating again the equal importance of temperature and time in producing the anomalous behavior. We note, however, that the  $M_H$  and  $M_T$  data overlap only above 21 K. The deviation at lower temperatures reflects the too-small field step (compared to  $H^*$ , as discussed above) in  $M(H, t)$  measurements. The small steps are not capable of "erasing" the previous flux profile and hence the time offset is ill defined.

In conclusion, our results demonstrate the absence of

the anomalous peak at  $t=0$  and the important role of vortex dynamics in the ability to observe this peak. The physical origin of the sharp crossover in the dynamics, observed over a relatively narrow field range, is still an open question. It may be another reflection of the presence of surface barriers which affect the dynamics and may even control it at intermediate temperatures and low fields. The importance of these barriers to the dynamics decreases with fields; A 400 Oe is a reasonable crossover field for the disappearance of surface barriers. Another possibility is that the sharp anomaly reflects the crossover from a single-flux regime to a collective one,<sup>3,4</sup> which occurs at relatively low fields (compared to the crossover field of Y-Ba-Cu-O and La-Sr-Ca-Cu-O) due to the stronger anisotropy in this system.<sup>18</sup> In this interpretation, and according to our results, there is no anomaly at  $t=0$ . The anomaly is a result of faster relaxation in the single vortex regime.<sup>9,18</sup> Finally, we cannot rule out the possibility<sup>19</sup> that the sharp crossover is related to the

melting transition. In the field-temperature phase diagram for HTS a liquid phase of flux lines has been predicted for fields slightly larger than  $H_{c1}(T)$ .<sup>18,20</sup> As the field is further increased, the system should enter a "solid" phase. Crossing the melting line would result in a sharp increase in the magnetization, especially if pinning is enhanced in the solid phase. In such a scenario one still has to understand the role played by dynamic effects which are described in this article. We maintain that the dynamics is essential for reorganization of the fluxons into a structure similar to that expected for a pure system. This process requires some characteristic time beyond which the transition becomes observable.

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<sup>17</sup>The scaling features suggest variable separation of time and temperature:  $F(T)G(t)$ . A plausible choice for this product is  $T \ln(t/t_0)$  as predicted by the collective creep theory (Ref. 9).

<sup>18</sup>For a review, see G. Blatter, M. V. Feigelman, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur (unpublished).

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