Anomalous magnetic behavior in $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals near the superconducting-transition regime

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We have observed anomalous magnetization hysteresis (virgin curve lying above the return leg and formation of a knot in the hysteresis) in $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) single crystals between T_c and T_c-6 K. We present the temperature evolution of this anomalous behavior. We argue that the observed anomaly is the manifestation of the fluctuation phenomena due to the layered structure and high anisotropy of BSCCO crystal.

The magnetic phase diagram of the mixed state of the oxide superconductors has proven to be a rich system with many physical phenomena playing a role. It has been found that thermal fluctuations,[1–3] pinning disorder, and dimensionality[4,5] are all important in the statics and dynamics of magnetic vortices. The $Bi_2Sr_2CaCu_2O_8$ (BSCCO) system, in particular, is very interesting because of its high anisotropy and two-dimensional (2D) behavior. It has been shown[6–8] that a Kosterlitz-Thouless (KT) type transition, manifested by the spontaneous creation of thermally induced free vortex-antivortex pairs, occurs just below T_c, confirming this system to be of 2D type over a large temperature region. Above a characteristic temperature, T^*, where the susceptibility becomes field independent, diamagnetic fluctuations[9–11] become very active. The recent conjecture[9] from the results of excess conductivity and diamagnetic fluctuation near T_c in BSCCO crystals clearly explains the presence of 2D fluctuations near T_c (above T^*). Our recent observation of unusual behavior in magnetization hysteresis[12] of BSCCO crystals near T_c becomes very fascinating and motivates us to investigate this magnetic anomaly more carefully.

The vortex structure in BSCCO crystals is regarded as 2D pancake vortices confined to the CuO_2 layers with weak interaction between interlayer pancakes by Josephson and magnetic coupling. The region below 30 K, where the irreversibility field grows rapidly, has been explained in terms of a dimensional crossover (3D to 2D).[13,14] In contrast to this a similar type of crossover has been again predicted[10] from the magnetic anomaly of BSCCO crystals near T_c. Others report that the region near T_c is largely dominated by the fluctuation effects[11,15] due to 2D free (unpinned) vortices. The large fluctuation-induced magnetization in quasi-2D BSCCO has received considerable attention.

In order to investigate such an intriguing vortex state near T_c, we have carried out precise magnetization measurements in several batches of BSCCO crystals grown in different laboratories. For comparison purposes, similar experiments were carried out in $YBa_2Cu_3O_{7-y}$ (YBCO) and Pb-Sr-Y-Ca-Cu-O (PSYCCO) crystals very near their T_c. Our observed magnetic anomaly (wrong sign of the hysteresis) was reproducible in all BSCCO crystals for magnetic field parallel to the *c* axis, whereas such anomaly was absent in YBCO and PSYCCO crystals, and even in BSCCO when the applied field is in the *ab* plane. We argue that the observed magnetization anomaly originates from the fluctuation phenomena occurring near T_c.

High-quality single crystals used for the present studies were grown by the self-flux method. The details of the crystal growth and its characterization have been described elsewhere.[8,9,16] The electron probe microanalysis and x-ray studies confirmed that the crystal is a single phase. Two BSCCO crystals from two different batches having T_c at 89 and 86 K, respectively, have been used for the measurements. Both crystals have a very sharp transition, having a width less than 1.5 K. The sharp transition demonstrates the uniformity of our crystals. The T^* of these crystals were ~ 87 K ($T_c = 89$ K) and ~ 84 K ($T_c = 86$ K), respectively. The magnetization measurements both parallel and perpendicular to the *c* axis of the zero-field-cooled (ZFC) BSCCO crystals were carried out using a superconducting quantum interference device (SQUID) magnetometer (Quantum Design MPMS5) with a 4 cm scan length to keep the field inhomogeneity minimum. To minimize the trapped field in the magnet, the measurements were done after the first cooling of the warm magnet and without raising the field more than 200 G after the first cooldown. Most of the results presented here are done in this condition. However, if the cold magnet is oscillated from a high field to zero, the magnet also traps the minimum field (<3 G). In that case also, the anomalous hysteresis results are reproduced. The typical size of the crystals is $1\times2\times0.03$ mm^3.

Figures 1 and 2 show the *M-H* curves in a magnetic field applied parallel to the *c* axis of the crystals at different temperatures just below T_c for two BSCCO (2212) single crystals having T_c's at 89 and 86 K, respec-

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tively. Both the figures show clearly an anomalous magnetization behavior described as follows. The *M-H* curves display the wrong sign of hysteresis (virgin curve lies above the return leg) within a certain temperature regime between T_c and T_c-6 K. The return leg crosses the virgin curve for positive fields with the crossover point being designated as a "knot" in the *M-H* curve. The field value of the knot increases as one moves below T_c. At temperatures below about T_c-6 K (83 and 80 K for respective crystals), the *M-H* hysteresis loops display the right sign of hysteresis throughout.

Figure 3 shows a set of *M-H* curves very near T_c for the BSCCO crystal having $T_c=86$ K in a magnetic field applied perpendicular to the *c* axis. In this case, the field penetrates into the CuO_2 layers and the formation of pancakes is not possible. It is interesting to note that in this field configuration, the magnetic anomaly observed in the $H\|c$ case does not exist.

If one just uses the hysteresis in the *M-H* curve to define the irreversibility line $H_{irr}(T)$, then for $H\|c$, H_{irr} rises as T nears T_c and this rise starts[10] close to T^*. We now take the view that the hysteresis above the field value

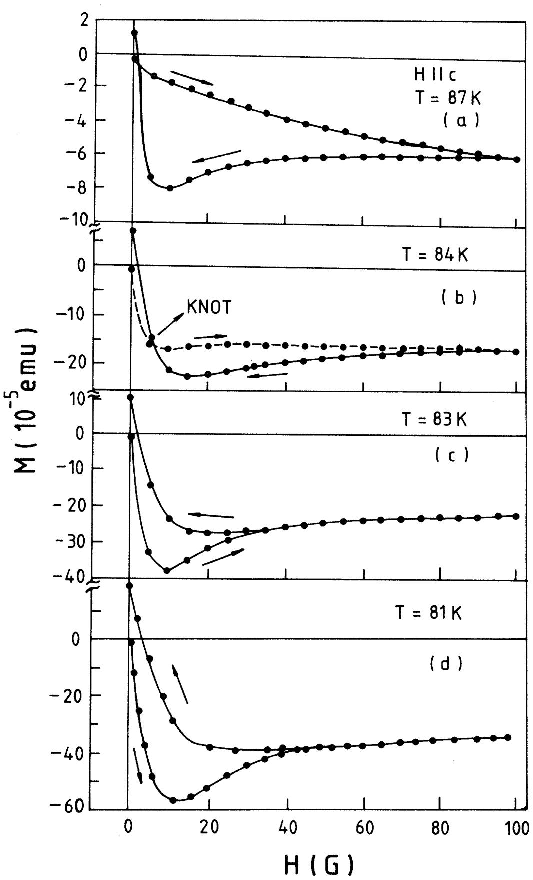

FIG. 1. *M-H* curves of single-crystal BSCCO with $T_c=89$ K, at various temperatures in a field applied parallel to the *c* axis. The formation of a knot is clear. The arrows show field increasing and decreasing branches.

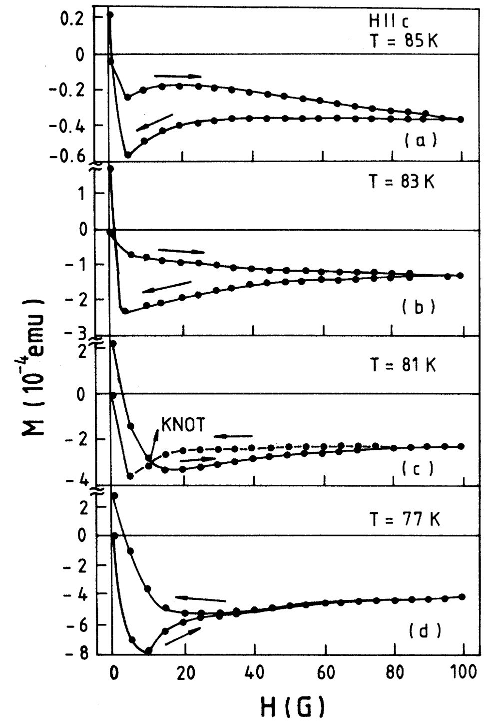

FIG. 2. *M-H* curves of single-crystal BSCCO with $T_c=86$ K at various temperatures in a field parallel to the *c* axis.

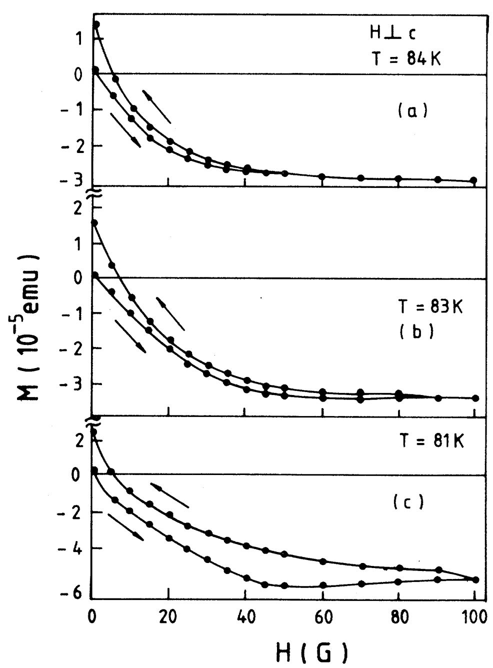

FIG. 3. *M-H* curves of a single-crystal BSCCO with $T_c=86$ K at various temperatures in a field perpendicular to the *c* axis.

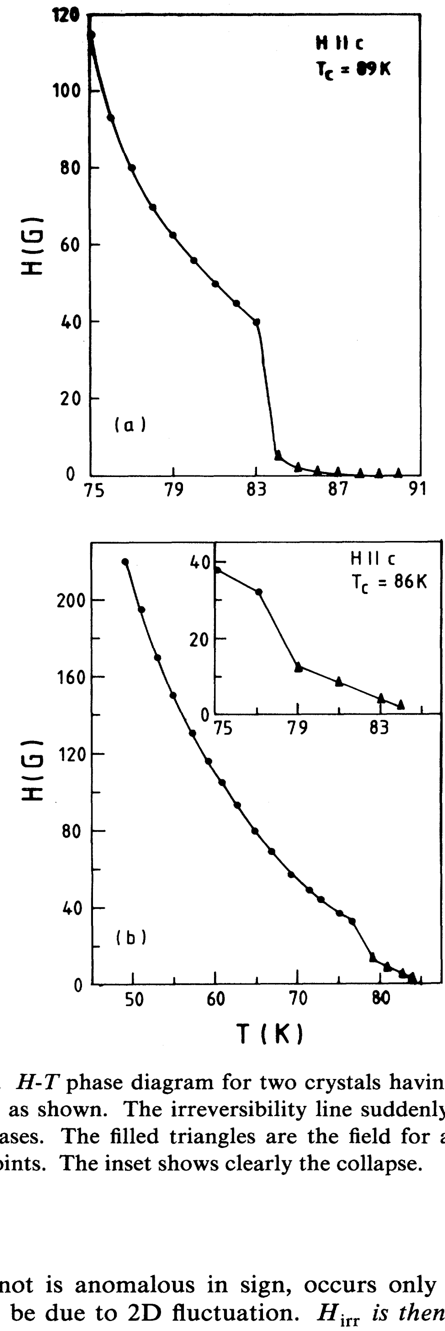

FIG. 4. H-T phase diagram for two crystals having T_c at 89 and 86 K as shown. The irreversibility line suddenly collapses in both cases. The filled triangles are the field for anomalous "knot" points. The inset shows clearly the collapse.

of the knot is anomalous in sign, occurs only for $H \| c$, and may be due to 2D fluctuation. *H_{irr} is then the field below which one sees hysteresis of the conventional sign.* Figure 4 shows the low-field irreversibility line for both crystals. We notice a sudden fall of the irreversibility line much below T_c. It may be noted that the filled triangles in Fig. 4 correspond to the knot formed by the wrong sign of the hysteresis curves. Therefore, this portion of the irreversibility line is anomalous. Brawner *et al.*[17] have shown from their magnetization measurements that in their BSCCO crystals, within 3 K below T_c, H_p (the field of the first flux penetration) and critical current density J_c are strongly suppressed. The extracted values of H_{c1} and J_c collapse to zero at a temperature $T < T_c$. This region of temperature near T_c is consistent with our temperature regime of observed magnetic anomaly.

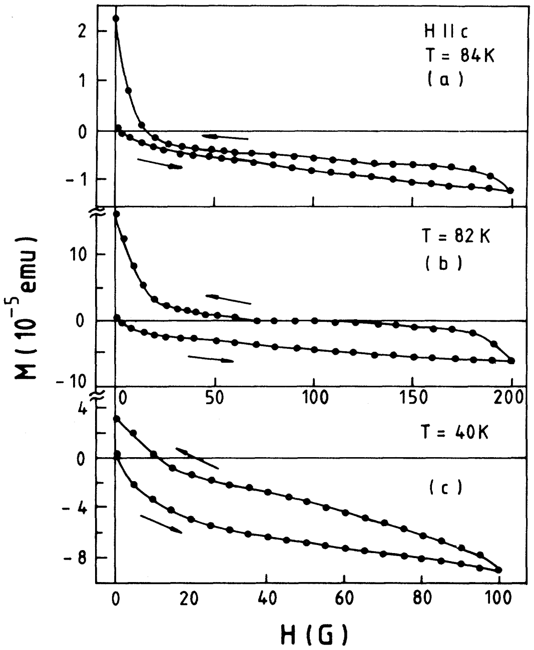

FIG. 5. M-H curves for an YBCO [(a) and (b)] and for a PSYCCO crystal [(c)] in a field parallel to the c axis for temperatures very close to their transition temperatures.

For a highly anisotropic material like BSCCO, the fluctuation conductivity and diamagnetic fluctuations near T_c have been explained in the framework of the Lawrence-Doniach model taking into account the weak interlayer Josephson coupling (JCLS). It is clear that as JCLS=0 a few degrees below T_c, the thermal creation of 2D vortices becomes fully operative giving rise to the KT transition. Once $T \geq T_{KT}$, the vortex-antivortex pairs are spontaneously generated and the conventional idea of flux expulsion becomes invalid. Collapsing of $H_{irr}(T)$ a few degrees below T_c predicts that $J_c = 0$ above this line. As BSCCO has CuO_2 layers linked by weak Josephson coupling between the layers, the layers become fully decoupled as JCLS=0. The thermal fluctuation of vortices in CuO_2 planes becomes very dominant, giving rise to various anomalies and a large diamagnetic fluctuation. In contrast to this, in pure YBCO crystals this region of temperature is extremely narrow and this type of fluctuation has not been observed. Moreover, the anisotropy in YBCO crystals is very small compared to that in BSCCO. The fluctuation phenomena related to the KT transition predicting the 2D nature are not observed near T_c.

There may be a possibility regarding the anomalous magnetization behavior observed in BSCCO being an experimental artifact of the SQUID magnetometer. We, therefore, have carried out similar magnetization measurements in YBCO (T_c=85 K) and PSYCCO (T_c=42 K) crystals just below their T_c's. We could not notice any such anomaly in these two crystals as shown in Fig. 5, though their magnetization values are of the same order of magnitude as in BSCCO crystals. We, therefore, rule out any possibility of experimental artifact due to SQUID measurements. To verify the consistency of the observed magnetization anomaly in BSCCO crystals, we used different batches of BSCCO crystals from different laboratories and we noticed the same magnetic anomaly reported here.

The absence of magnetic anomaly in BSCCO crystals when the field is applied parallel to the *ab* plane indicates that such anomaly is manifested in the CuO_2 layers. It is true that diamagnetic fluctuation is drastically decreased when the field is oriented parallel to the *ab* plane. Moreover, the pancakes are not formed when the field is parallel to the *ab* plane. Therefore, the fluctuation phenomena in the *ab* plane resulting from the layered structure and high anisotropy may be one possible origin of the anomaly observed for field perpendicular to the *ab* plane. Furthermore, the observed anomaly is in contrast to the phenomena due to the surface barrier,[18,19] where almost zero magnetization of the descending branch is one of the main fingerprints of the Bean-Livingston surface barrier.

In conclusion, we argue that the observed magnetic anomaly (virgin curve lying above the return curve) in BSCCO single crystals near T_c is a manifestation of fluctuation phenomena. However, detailed experimental and theoretical works are needed for the explanation of such anomalous behavior in magnetization.

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