# Critical State of the Weakly Coupled Two-Dimensional Superconductor $Bi_2Sr_2CaCu_2O_8$

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Transport measurements show that the critical current in the $c$ direction, $J_c^c$, of $Bi_2Sr_2CaCu_2O_8$ single crystals increases with temperature for low temperature zero field cooled (ZFC) measurements. As a consequence, the $c$ direction electrical resistance of the ZFC critical state, at a given dc current, is finite, goes to zero with increasing temperature, and becomes finite again at higher temperatures. The results are consistent with a loss of the $c$ axis long range correlation induced by the critical current flowing in the $ab$ planes, $J_c^{ab}$, and an increase of that correlation with temperature, as a consequence of the corresponding decrease of $J_c^{ab}$.

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The magnetic response of the flux structure of $Bi_2Sr_2CaCu_2O_8$ single crystals (BSCCO) when the dc magnetic field is applied parallel to the $c$ direction shows quasi-two-dimensional character in a large fraction of the $H$-$T$ phase diagram. This has been demonstrated by recent ac [1–3] as well as dc magnetic experiments [4] and transport [5, 6] experiments. The dc magnetization measurements [4] show that the thermodynamic reversible region is reached at a temperature $T_I(H)$, several degrees above a second temperature $T_M(H)$ of the order of 20 K where the critical current associated with the $ab$ planes, $J_c^{ab}$, collapses to very small but finite values. The two-dimensional behavior [1, 2, 4] of the vortex structure in the range of temperatures $T_M(H) < T < T_I(H)$ has been reconfirmed [3] by the presence of a dissipation peak in the imaginary component of the ac susceptibility $\chi''$, that is shown to lie well below $T_I(H)$ for frequencies as low as 7 Hz. This peak is observed in a configuration where a dc field, $H_{dc}$, is applied parallel to $c$ and an ac field, $\mathbf{h}_{ac}$, perpendicular to this direction. In the more usual configuration, where $\mathbf{h}_{ac}$ is parallel to $c$, the dissipation peak lies [2, 3] above the irreversibility line $T_I(H)$. Within the previously described picture of the $H$-$T$ phase diagram the critical current in the $c$ direction, $J_c^c$ , should be zero above $T_M(H)$, in agreement with recent critical current measurements [7]. The three-dimensional character of the vortex system of the BSCCO compounds must then be restricted to a small temperature region below $T_M(H)$.

Considering the characteristics of the phase diagram we expect to find a true zero electrical resistance [8] only below $T_M(H)$. Thus, it is interesting to ask whether the superconducting critical state for $T < T_M(H)$ can be described by the same model used for traditional three-dimensional superconductors or, on the contrary, is determined by the two-dimensional character of the pancake vortices [9] nucleated in the $ab$ planes.

In this Letter we report an experimental study of the behavior of the critical state of BSCCO through dc and ac transport measurements. The results make evident that the two-dimensional characteristics of the system play a fundamental role in determining the vortex configuration in the mixed state.

The work presented here was stimulated by preliminary data obtained by mechanical oscillator experiments [10]. In Ref. [10] it was found that the zero field cooled (ZFC) response at low temperatures corresponded to a vortex lattice softer than that in field cooled (FC) measurements and, rather remarkably, the ZFC data approached the FC values when temperature was increased.

We have used the mutual inductance technique [2] to investigate the ac response of BSCCO single crystals in two different configurations. $H_{dc}$ is always parallel to the $c$ axis, while $\mathbf{h}_{ac}$ is applied perpendicular to the $c$ axis in one case and parallel to it in the other. We show that at low temperatures, the ZFC and FC ac responses are different in the former case (ac currents induced across the $ab$ planes) and yet are the same for the latter case (ac currents flowing in the planes).

A qualitative interpretation of the ac response, based on a picture where vortices are two dimensional, coupled through magnetic and Josephson interactions, led us to perform dc transport critical current measurements in the $c$ axis direction in order to investigate the hypothesis that the low temperature critical state is different from that of a traditional three-dimensional vortex configuration.

The single crystal used in the ac susceptibility measurements was the same as that used in Ref. [2]. The single crystal used in the transport experiment (of dimensions 1 mm × 1 mm × 30 $\mu$m) was grown by directional solidification [11]. The contact configuration is similar to the one reported by Briceño *et al.* [12]. The current is injected and removed by well aligned gold sputtered ring

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shaped pads located on opposing faces of the sample, in order to ensure that the macroscopic current distribution in the $c$ axis direction is homogeneous. The voltage drop is measured between pads positioned concentrically to the rings at the center of the crystal. The area of the voltage contacts was $\sim (100\,\mu\mathrm{m})^2$, while the current contacts covered more than 70% of the total sample area. Low resistance contacts ($\sim 1\ \Omega$) were obtained by following the method described in Ref. [5]. From the $c$ axis resistive transition ($\rho_c$), at zero applied magnetic field we obtain $T_c^{\mathrm{onset}} = 86.5$ K, $\Delta T_c = 2.35$ K, and the midpoint of the transition at 85.5 K. The behavior of $\rho_c(T, H)$ for $T < T_c$ and $H < 4$ T is found to be in good agreement with other published data [12, 13].

Figure 1 shows the real component of the ac susceptibility $\chi'$ of BSCCO as a function of temperature in FC and ZFC experiments at different magnetic fields. In this case $H_{\mathrm{dc}}$ is applied parallel to $c$ while $\mathbf{h}_{\mathrm{ac}}$ is perpendicular to $c$. The difference between the ZFC and FC $\chi'$ at low temperatures is evident. This difference is found to be independent of frequency and amplitude of the ac field, in the range between 100 Hz and 10 kHz and from 10 mOe to 1 Oe. The imaginary component of the susceptibility shows very little dissipation in the range of temperatures where the ZFC and FC data are different.

Experiments performed in a geometry where $\mathbf{h}_{\mathrm{ac}}$ is parallel to $H_{\mathrm{dc}}$ yield the same value of $\chi'$ for ZFC and FC over the whole temperature range. Since this is what is expected for the ac response of three-dimensional pinned vortices, when the ac amplitude is too small to unpin them, we focus our attention on the other ac field configuration where the results cannot be explained by the traditional picture.

In the ZFC case for $\mathbf{h}_{\mathrm{ac}} \perp c$ $\chi'$ is history dependent as shown in the inset of Fig. 1. This illustrates that when ac currents flow across the $ab$ planes, $\chi'$ depends on the dc magnetic flux configuration induced in the ZFC experiment. This result, together with the ac field amplitude independence of the susceptibility, rules out any conventional explanation based on present critical state models. There is no field history dependence when $\mathbf{h}_{\mathrm{ac}} \parallel c$ , which strongly implies that the low temperature decrease of the ZFC shielding capability when $\mathbf{h}_{\mathrm{ac}} \perp c$, must be related to the interplane ac currents.

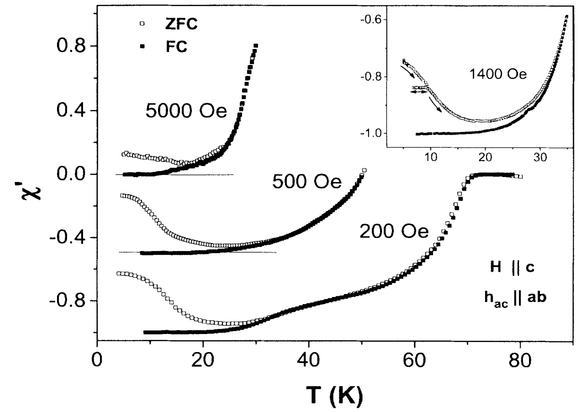

FIG. 1. $\chi'$ as a function of temperature for different dc magnetic fields. For the sake of clarity the curves corresponding to 500 and 5000 Oe have been offset. The inset shows the history dependence of $\chi'$ on different temperature cycles.

The reduction of the ZFC ac shielding ($\chi'$) without a corresponding increase of the dissipation ($\chi''$) indicates that the superconducting ac currents flow in restricted regions of the sample. However, as was mentioned before, there is no shielding reduction in FC experiments and neither in ZFC nor in FC when the ac currents flow in the $ab$ planes. This shows that the ZFC reduction of the superconducting volume where ac superconducting currents flow is determined by the appearance of resistance in the $c$ direction in some regions of the sample. In this sense, although the average field is only in the $c$ direction the critical current is induced in the $ab$ planes as well as in the $c$ direction. The history dependence of $\chi'$ on temperature cycles strengthens this supposition, since it is locked to a value which corresponds to the ZFC flux structure state established at the highest temperature of the last cycle.

The current distribution associated with the critical state in the ZFC experiment induces an inhomogeneous force on the pancake vortices that can destroy the vortex long range correlation in the $c$ direction, at least in some regions of the sample. If this were the case the resistance in the $c$ direction of those regions should be different from zero and probably quite large. In this sense the ZFC experiment resembles that of the pseudo dc transformer [5, 6]. In the former the inhomogeneous current distribution is induced as a consequence of sample geometrical effects rather than by injecting a nonhomogeneous current.

In the FC experiments the vortex structure pinned at high temperatures has a rather homogeneous flux distribution and consequently a much smaller induced current density. In the ZFC experiments the force acting on the vortices for a given dc field is determined by the critical current flowing in the $ab$ planes. However, the critical current decreases [4] strongly with temperature and therefore the forces exerted on the pancake vortices become weaker. As a consequence of this, the effective correlation length in the $c$ direction could increase with temperature in a large fraction of the sample, explaining the increase of shielding capability as the temperature is increased.

With these ideas in mind we decided to perform new and independent $c$ axis critical current measurements to check the suggested novel picture of the critical state, based on the coexistence of two flux structures: pancake vortices nucleated in the $ab$ planes and Josephson vortices between them. Within the proposed picture of the ZFC critical state a decrease of the $ab$ critical current reduces the inhomogeneous displacement of vortices in the $ab$ planes and therefore the induced Josephson currents between *ab* planes. Thus, $J_c^c$ could in principle increase with temperature. It is important to point out that this *c* axis critical current, in a configuration where there is no Lorentz force on the pancake vortices, should be associated with the lack of phase coherence between *ab* planes.

Figure 2 shows a series of *I*-*V* characteristics for different temperatures at an applied field of 1 T. The sample was cooled in zero field, the field was applied at constant temperature, and then the *I*-*V* curve was measured. After this, with no current applied, the temperature was slowly raised to the new desired value, after which the new *I*-*V* curve was measured. Care was taken to avoid any overshoot during the temperature increase. A well defined critical current is evident from the data in the figure [14]. The critical current $I_c^c$ is defined with a 50 nV criteria on the voltage contacts of the sample and the error in the determination is less than 0.5 mA in the whole temperature range investigated.

At low temperatures [Fig. 2(a)] the critical current increases with increasing temperature, as predicted from the previous discussion. However, the experimental data show that $I_c^c$ goes through a maximum and then decreases as the temperature is further increased, as can be seen from Fig. 2(b). Notice that the maximum in $I_c^c$ does not depend on the criteria used to define it. It reflects that the *I*-*V* curves are displaced first towards higher currents and then towards lower currents with increasing temperature.

Some comments are appropriate concerning the *I*-*V* characteristic curves in Fig. 2. It is interesting to notice the almost discontinuous change of the voltage at $I_c^c$ in the range of temperatures close to where $I_c^c$ is maximum. The *I*-*V* characteristics are reversible with current in the low and high temperature region but irreversibilities are measured in the temperature regions where the jump in the voltage is detected [15]. We do not associate the jump in voltage to power being dissipated either in the sample or in the current contacts, as is clearly demonstrated by comparing curves for different temperatures. The results reported here correspond to those for the increasing current direction only.

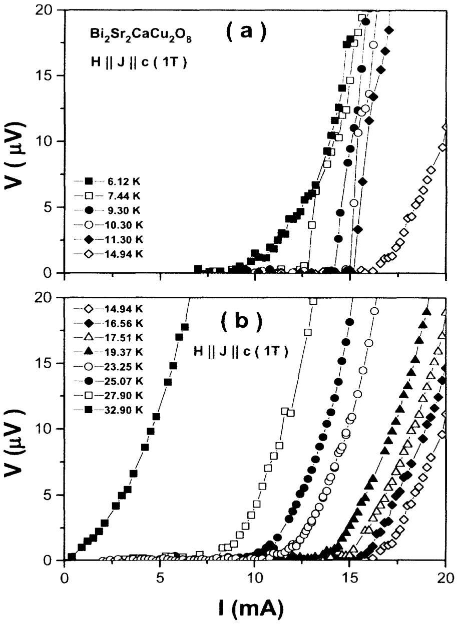

FIG. 2. *I*-*V* characteristic of BSCCO for $H_{dc} = 1$ T, at different temperatures. The lines are a guide to the eye. *I*-*V* curves corresponding to critical currents (a) increasing with temperature and (b) decreasing with temperature. In both cases $H_{dc} \parallel J \parallel c$ axis.

Similar results to those shown in Fig. 2 were found for the other fields investigated of 0.5 T, 2 T, and 3 T. The temperature dependence of the ZFC critical current density $J_c^c$ in the *c* direction, defined as $I_c^c$ divided by the area of the sample, for the different applied fields is plotted in Fig. 3. The increase of the critical current with temperature in the low temperature region is noticeable for all fields investigated.

This unusual increase of $J_c^c$ with temperature is the result of two competing effects: the distortion of the vortex lattice due to the inhomogeneous force induced by the currents in the *ab* planes and the decrease of the force gradient in the *c* direction associated with the decrease of $J_c^{ab}$. Thus, $J_c^c$ is an increasing function of temperature up to a temperature somewhat lower than $T_M(H)$ [1, 2, 4], where the thermal disorder begins to dominate and the critical current decreases, as observed in Fig. 3.

The results of Fig. 3 suggest that, if for a given field, the resistance of the mixed state in the *c* direction is measured with a current density lower than the corresponding maximum value of $J_c^c$, a striking effect can be found. Figure 4 shows the ZFC out-of-plane electrical resistance $R_{c\text{-axis}}$ as a function of the temperature for 2 T, for a measuring current indicated by the dashed line in the inset of the same figure: $R_{c\text{-axis}}$ is finite at low temperatures, goes to zero when increasing temperature,

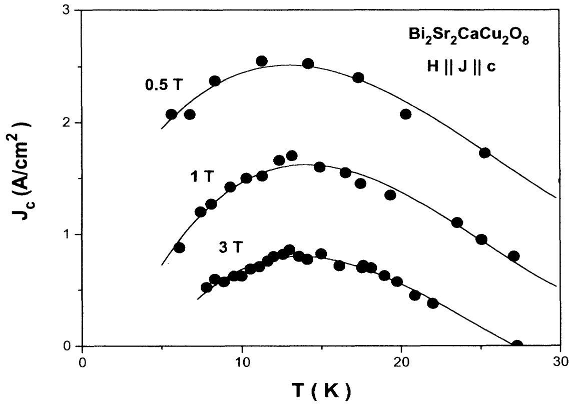

FIG. 3. Temperature dependence of the ZFC $J_c^c$ for different applied magnetic fields. The lines are a guide to the eye.

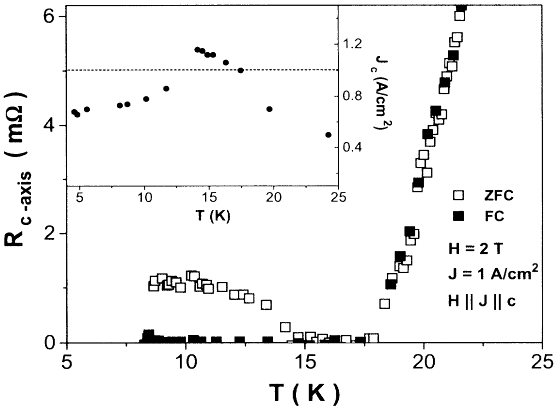

FIG. 4. ZFC and FC out-of-plane resistance as a function of temperature for $H_{\rm dc} = 2$ T. The inset shows $J_c^c$ for the same dc field as a function of temperature. The dashed line indicates the value of the current density used in the main figure.

and becomes finite again at higher temperatures. For comparison, the FC resistance for the same current is also plotted. The behavior at low temperatures, where the ZFC and FC resistances differ, is consistent with the corresponding observation of a large FC critical current. For example, at 5 K, no voltage was detected up to currents as large as 2 times the maximum value reached by the ZFC critical current.

It is interesting to point out that the results reported in this work have been obtained in crystals of different origin and somewhat different characteristics, showing that the main features of the magnetic response are general properties of these materials, independent of the particular characteristics of a given crystal. The experimental results appear to demonstrate that it is the quasi-two-dimensional character of the vortex state in the BSCCO compounds which determines the characteristics of the critical state. The results show that the inhomogeneous distribution of currents in ZFC experiments induces a critical state where the two-dimensional character of the system becomes important in the otherwise three-dimensional region of the *H*-*T* phase diagram.

The experiments have discovered the rather unusual situation of two different critical currents competing to determine the overall characteristics of the magnetic response of the oxide superconductors: While it is well known that $J_c^{ab}$ decreases with temperature $J_c^c$ is seen to increase up to a maximum where the thermal disorder decreases the correlation in the *c* direction. The decrease of the *c* axis critical current with temperature after reaching its maximum demonstrates the importance of the thermally induced disorder [16] in reducing the correlation length in the *c* direction. In conclusion, the results reported here show clearly that the critical state induced by a magnetic field perpendicular to the *ab* planes is characterized by the coexistence of two different types of current, one giving rise to a metastable vortex state and the other inducing energy dissipation in the nonsuperconducting regions between the *ab* planes. The two-dimensional characteristics of the vortex system, made evident by magnetization [4], transport [5], and low frequency susceptibility measurements [3], are shown to determine the main characteristics of the critical state in the low temperature region of the phase diagram. These results raise questions regarding the nature of the critical state, the vortex models used to calculate the critical currents and magnetization, the character of magnetic excitations and their contribution to the possible melting transition of the vortex structure. More experimental as well as theoretical work is necessary to provide a definitive answer to these questions.

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[1] C. Durán *et al.*, Phys. Rev. B **44**, 7737 (1991).
[2] J. Yazyi *et al.*, Physica (Amsterdam) **184C**, 254 (1991).
[3] A. Arribère *et al.* (unpublished).
[4] H. Pastoriza *et al.*, Phys. Rev. B **46**, 9278 (1992).
[5] H. Safar *et al.*, Phys. Rev. B **46**, 14 238 (1992).
[6] R. Busch *et al.*, Phys. Rev. Lett. **69**, 522 (1992).
[7] M. F. Crommie *et al.*, Phys. Rev. B **45**, 13 148 (1992).
[8] D. S. Fisher *et al.*, Phys. Rev. B **43**, 130 (1991).
[9] J. R. Clem, Phys. Rev. B **43**, 7837 (1991).
[10] C. Durán *et al.*, in *Proceedings of the ICTP'90 International Conference on Transport Properties of Superconductors, Rio de Janeiro, Brazil, 1990*, edited by R. Nicolsky (World Scientific, Singapore, 1990), p. 146.
[11] D. B. Mitzi *et al.*, Phys. Rev. B **41**, 6564 (1989).
[12] G. Briceño *et al.*, Phys. Rev. Lett. **66**, 2164 (1991).
[13] A. Kapitulnik, in *Phenomenology and Applications of High Temperature Superconductors*, edited by K. Bedel *et al.* (Addison-Wesley Publishing Company, Reading, MA, 1992), p. 34; K. Kadowaki, in *Electronic Properties and Mechanisms of High Tc Superconductors*, edited by T. Oguchi, K. Kadowaki, and T. Sasaki (Elsevier Science Publishers B.V., Amsterdam, 1992).
[14] Although the abrupt change of the voltage induces to think of an excellent definition of $I_c^c$, it is necesary to recall that, due to the geometrical factor of this configuration, if 50 nV is taken as the voltage sensitivity, the definition of the critical current from our data is equivalent to use a 100 $\mu$V criterion for a sample 1 cm long.
[15] E. Rodríguez, M. F. Goffman, A. Arribère, and F. de la Cruz (unpublished).
[16] L. L. Daemen *et al.*, Phys. Rev. B **47**, 11 291 (1993). In this reference the importance of thermally induced disorder in a homogeneous field distribution is discussed in terms similar to those used throughout the paper.