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In- and out-of-plane vortex correlations in $YBa_2Cu_3O_7$

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Transport measurements in the mixed state of $YBa_2Cu_3O_7$ crystals ($H\|c$) using the "dc-flux-transformer" configuration show that the glass-liquid phase transition at the irreversibility line, $T_i(H)$, behaves as a three-dimensional vortex phase transition. These results together with resistance measurements in the c direction show that the vortex correlation across the sample is destroyed at a temperature $T_{th}(H)$, higher than $T_i(H)$. However, the dependence of $T_{th}(H)$ on sample thickness suggests that, in real thermodynamic phase transitions (infinite sample), the long-range correlation in the ab plane, as well as in the c direction, is lost at the single temperature $T_i(H)$.

The high-temperature oxide superconductors have provided the opportunity to study the influence of thermal fluctuations in different topological configurations of the vortex structure. The controversial work by Gammel *et al.*[1] identifying the irreversibility line separating the reversible from the nonreversible thermodynamic region as the locus of a thermodynamic phase transition has received strong experimental and theoretical support.[2,3] However, many unknowns are yet to be resolved before a complete phase diagram of the oxide superconductors can be drawn.

When the superconducting coupling between planes is moderately strong many characteristics of the magnetic response are explained using the anisotropic Ginzburg-Landau theory.[4] This is believed to be the case of the $YBa_2Cu_3O_7$ [YBCO(123)] compound. When the coupling is very weak the two-dimensional (2D) character of the vortices (pancakes[5]) has to be taken explicitly into account.[4] This is the case for $Bi_2Sr_2CaCu_2O_8$ [BSCCO(2212)].

In principle, two symmetries could be broken in a vortex structure, one related to the loss of long-range superconducting order in the direction of the applied field and the other associated with the loss of the phase coherence in the topological vortex distribution.[4,6,7] In the case of BSCCO(2212), for $H\|c$, there is a crossover field[8–10] $B_{cr}\cong 350$ G. Above it the sample shows superconducting laminar characteristics and below it an anisotropic three-dimensional behavior. At low temperatures and $B>B_{cr}$ the vortex structure is ordered and the 3D character is shown by the lack of electrical dissipation in all directions.[11,12] When the temperature is increased the superconducting long-range order in the field direction is lost, inducing a 2D vortex structure that remains pinned up to the irreversibility line. Whether one or both lines represent thermodynamic transitions is not known.[4,7,13] When $B<B_{cr}$ the three-dimensional character of the vortex structure is made evident and the long-range order is lost through a first order thermodynamic transition.[10] The vortex structure in YBCO remains 3D up to the irreversibility line, $T_i(H)$, where, through a thermodynamic first[14] or second[15] order phase transition (depending on disorder) the system loses the long-range order in the ab plane.

The two-dimensional character of the vortex structure of BSCCO has been detected[16,17] through resistivity measurements using a dc-transformer electrical contact configuration.[18] The same technique has shown[19–21] that in YBCO the transition at $T_i(H)$ is a 3D-3D vortex transition. However, a 3D-2D thermally induced transition is also detected[19–21] at higher temperatures.

In a recent paper, Feigelman and co-workers[6] have predicted an H-T phase diagram for YBCO(123) where the solid vortex lattice loses the long-range translational order through a thermodynamic phase transition at $T_{melt}(H)$. The phase just above $T_{melt}(H)$ is predicted to be a 3D vortex liquid phase with zero electrical resistance in the field direction and separated from the uncorrelated normal state through another genuine phase transition. This behavior is similar to that mentioned in the preceding paragraph and reported in Refs. 19–21. On the other hand, in those references the study of the electrical response was concentrated on the behavior of the electrical resistance in highly nonuniform current configurations where the linear nonlocal[24] electrodynamic response was detected.

In this paper we study the behavior of the electrical resistivity in the c direction in twinned YBCO(123) single crystals to determine whether the loss of the long-range superconducting order in the direction of the field is a thermodynamic phase transition. To avoid or at least diminish the effects of the nonlocal electrical response, the current in the c direction is induced in an electrical configuration that assures a more homogeneous current injection than that used in Ref. 19. We compare the features observed in this configuration with those obtained using the nonhomogeneous dc transformer configuration. In particular, the I-V characteristics show that there is no linear response in the c direction in the temperature region where there is 3D vortex correlation in the field direction. This strongly suggests the existence of a region in the phase diagram where $\rho_c=0$ and $\rho_{ab}\neq 0$, above $T_i(H)$. It is shown that while the transition at $T_i(H)$ has the characteristics of a thermodynamic phase transition, the loss of phase coherence in the c direction takes place at a temperature determined by sample dimensions.

The results reported here correspond to crystals heavily twinned as those of Refs. 19 and 21. The single crystals were grown as described in those references. The typical dimensions of the samples were $1\times 0.5\times 0.03$ mm^3. The electrical measurements were made using standard dc techniques. Typical contact resistances were $<1\ \Omega$. The quality of the

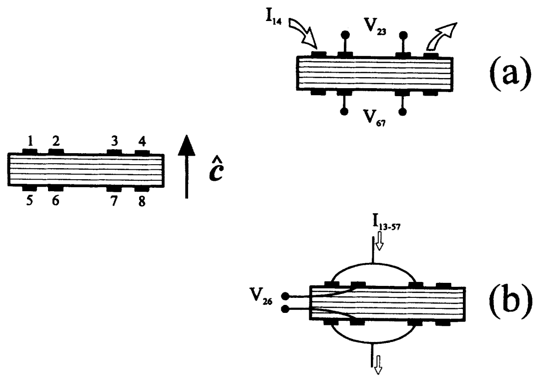

FIG. 1. Sample electrode geometry (left) and current configurations used in this paper. (a) "flux transformer" geometry: the current is applied between terminals 1 and 4 (I_{14}) and the voltage is measured between 2 and 3 (V_{23}) and 6 and 7 (V_{67}). In this configuration the current is injected primarily parallel to the ab planes. In the c-axis measurements (b), the current is injected using the contacts 1 and 3 and is removed through the electrodes 5 and 7 on the opposite face (I_{13-57}). In this way a uniform current distribution parallel to the c axis is induced.

samples is checked using the contact distribution shown in Fig. 1. It is found that $V_{23}(I_{14})=V_{67}(I_{58})$ and $V_{67}(I_{14}) = V_{23}(I_{58})$ within 10%. The electrode distribution in the transformer configuration is shown in Fig. 1(a). The measurements of the resistance in the c direction were made feeding current, I_{13-57}, through contacts 1–3 and removing it through 5–7. The voltage was measured between 2 and 6; see Fig. 1(b). Due to the unfavorable geometrical factor of the samples, the Ohmic resisitivity in the c direction at low temperatures can only be measured down to values that are not lower than those of copper at room temperature, $\rho_{Cu}=1$ $\mu\Omega$ cm.

Figure 2 shows typical results of the in-plane resistance (defined as $R_{ij}=V_{ij}/I_{14}$) vs temperature for two samples using the transformer configuration. The measurements reported in this paper were made above the irreversibility line and for fields applied in the c direction. The results for other fields have similar features as those shown in Fig. 2 for $H=10$ kOe. In order to assure the I-V linear response,[20,21] the data were taken using low current densities. Two different regimes are detected, one for $T>T_{th}$, where the vortex velocity on top of the sample is larger than that at the bottom ($R_{23}>R_{67}$), and the other below T_{th}, where the vortex velocity is the same across the sample ($R_{23}=R_{67}$). The results show that thermal energy induces two-dimensional behavior of the vortex structure above T_{th}.

Figure 3 shows the resistance in the c direction, $R_c=V_{26}/I_{13-57}$, as a function of I for different temperatures at $H=10$ kOe, using the configuration indicated in Fig. 1(b). An Ohmic regime is observed at high temperatures and low currents. The range of currents where the response is Ohmic is rapidly reduced when decreasing temperature and a transition from a linear to a nonlinear behavior is evident at a well defined temperature. The value for R_c in the linear regime as a function of temperature is plotted in Fig. 2. The results show that the smallest measurable $R_c \cong 5\times10^{-6}$ Ω, is found above T_{th}. The drop of R_c at a rate of one order of

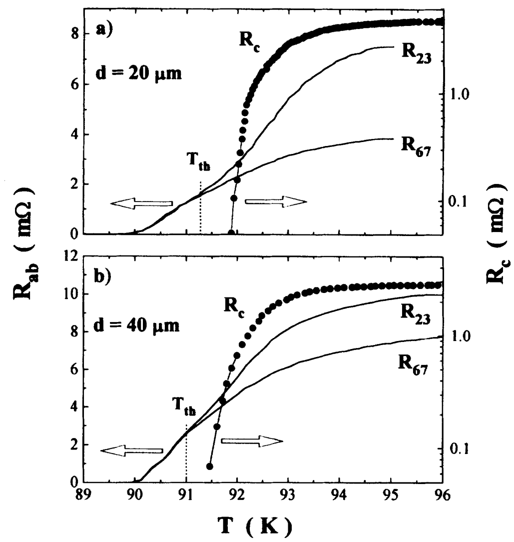

FIG. 2. Shown are the measured temperature dependences of the in-plane (R_{23} and R_{67}) and out-of-plane (R_c) resistances for $H=10$ kOe parallel to the c axis. The upper panel (a) corresponds to a sample thickness of 20 μm and the lower panel (b) to one of 40 μm. The dashed line shows the values of T_{th}. Notice the logarithmic scale for R_c.

magnitude per 0.1 K and the nonlinear response, see Fig. 3, suggest a true zero resistance state at $T=T_{th}$, $\rho_c(T_{th})=0$, indicating the possible presence of a phase transition.[6,22] If this were the case, the superconducting long-range order in the c direction would be achieved at a temperature well above that where the long-range order in the ab plane has been established,[3,23] $T_i(H)$. However, the experimental data of Fig. 2 and those of Refs. 19 and 21 show that T_{th} is sample thickness dependent. This is not surprising since, from the definition, at T_{th} the superconducting correlation length in the direction of the field coincides with the sample thickness. From this point of view the phase transition in the c direction is frustrated by the finite dimension of the sample. As a result, we can map the temperature dependence of the superconducting correlation length in the c direction varying the sample thickness.

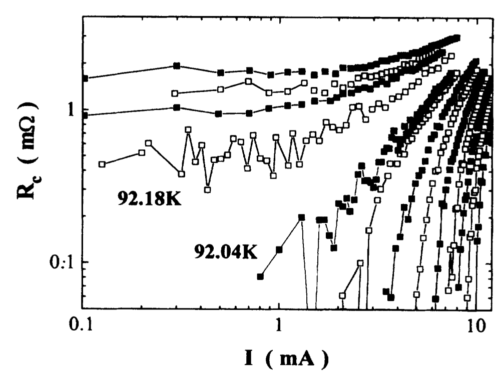

FIG. 3. Shown is R_c as a function of measuring current I_{13-57} [see Fig. 1(a)] for different temperatures and $H=10$ kOe, for $d=20$ μm sample. The curves correspond to $T=92.82$, 92.68, 92.27, 92.18, 92.04, 91.89, 91.75, 91.62, 91.48, 91.37, 91.23, 91.08, and 91 K from top to bottom.

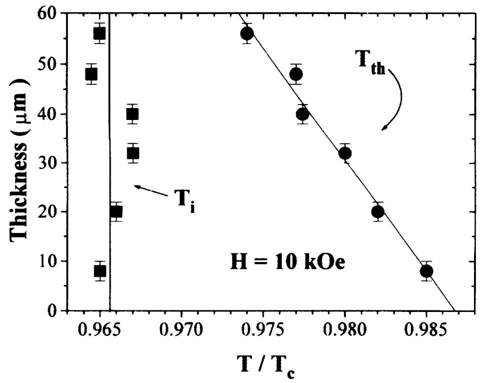

FIG. 4. The thickness dependence of the temperatures T_i and T_{th} (see text) for $H=10$ kOe parallel to the c axis. The solid line is to guide the eye.

In Fig. 4, T_i and T_{th} are plotted for samples of different thicknesses. The thickness independence of $T_i(H)$, defined as the temperature where the I-V curves in the ab planes have a power law in the whole range of current, is consistent with the establishment of long-range order in the direction perpendicular to the applied field[23] through a thermodynamic phase transition at this temperature. In this sense the sample dimensions in the ab plane (1 mm) are large enough to consider them as infinite. However, the decrease of T_{th} when increasing thickness suggests that T_{th} represents the temperature dependence of a correlation length in the c direction growing as T approaches $T_i(H)$.

In a recent Letter[19] it has been shown that the electrodynamics of a vortex liquid state has a nonlocal character.[24] The arguments used to demonstrate the nonlocal electrical behavior were based on the Ohmic reponse of the liquid in all crystallographic directions. Our results suggest that in an infinite sample the electrodynamics would be linear and nonlocal down to $T_i(H)$. Since a perfectly uniform current distribution cannot be assured, our results of ρ_c can be affected by the nonlocal response at temperatures close to $T_{th}(H)$. On the other hand, comparing this data with those extracted from the dc-transformer configuration using the Montgomery type of analysis it is found that the qualitative behavior of ρ_c with temperature is the same in both configurations. Small quantitative discrepancies can be attributed to geometrical uncertainties. Thus, although nonlocal effects in ρ_c cannot be completely ruled out, they do not affect the relevant result of this paper showing the appearance of nonlinearity in the electrical response in the c direction well above the temperature $T_i(H)$ where the linear response in the ab plane is established.

The main contribution of this work is to show that in the available samples, with thicknesses in the order of several μm, the phase transition at the irreversibility line looks like a 3D-3D vortex transition. In this case there is a finite temperature range, $T_i(H)<T<T_{th}(H)$, where the vortex liquid phase has $\rho_c=0$ and $\rho_{ab}\neq 0$. On the other hand, the thickness dependence of the temperature where thermally induced vortex decoupling takes place suggests that in the real thermodynamic phase transition (infinite sample) the long-range correlation in the ab planes as well as in the c direction is lost at the single temperature $T_i(H)$. In this sense the phase diagram of YBCO is similar to that recently reported[10] for BSCCO(2212) for fields under 350 Oe, where the long-range correlation of the vortex structure in all directions is lost in a 3D-2D vortex transition, in qualitative disagreement with the predictions of Ref. 6.

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