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Two-step liquid-solid vortex transition with the field along the *ab* planes in $YBa_2Cu_3O_{7-\delta}$ crystals

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Resistivity measurements for different Lorentz force configurations and the detection of the longitudinal vortex velocity correlation length, with the magnetic field applied parallel to the *ab* planes, in the mixed state of clean and twinned $YBa_2Cu_3O_{7-\delta}$ single crystals, support the existence of a vortex-smectic phase when the vortices interact with an attractive periodic potential. The transition from the vortex-liquid to the vortex-solid state is shown to be achieved in two steps, a continuous transition from a liquid to a possible smectic phase and another continuous one from the smectic phase to a solid. [S0163-1829(99)09413-8]

The discovery of different phases in the vortex system of high-T_c superconductors has drawn renewed attention on the study of phase transitions in condensed-matter physics.[1] In spite of their similarity with systems of interacting particles a different ingredient is added to the problem, namely the interaction with defects in the embodying material which act as attractive centers. This effect cannot be treated as a perturbation but changes the behavior of the entire system.[2,3] Indeed, the first-order solid-to-liquid phase transition observed in clean high-T_c superconductors[4–7] transforms into a second-order glass to liquid transition when the effect of the disorder potential dominates.[8,9] Further studies showed that the nature and the spatial correlation of the defects alter the properties of the liquid phase, particularly the vortex velocity correlation length.[10,11]

An interesting case, which has a realization in the layered structure of the high-T_c superconductors, is that of a periodic planar potential treated by Balents and Nelson.[12] The confinement induced by these potentials (with periodicity s) is restricted to one spatial direction and consequently the transverse wandering of the vortex lines in that direction is significantly decreased. Thus, on cooling, a positional long-range order of the vortex structure may be established in the direction perpendicular to the Cu-O planes while it remains disordered within them. Based on this simple argument two different transitions are expected to occur,[12] one from a liquid to a ''smectic phase'' in which vortices are arranged with periodicity a in the direction perpendicular to the planes, and at a lower temperature another transition to a crystalline solid. The vortex-liquid to smectic transition is expected to be second order given its similarity with the nematic smectic-A transition discussed by De Gennes.[13]

The theoretical work of Balents and Nelson was triggered by the experimental results obtained by Kwok *et al.*[14] who studied $YBa_2Cu_3O_{7-\delta}$ single crystals with the magnetic field oriented parallel to the *ab* planes. They analyzed the dynamical response of the vortex structure near the temperature where the resistivity (ρ) goes to zero. They found that the abrupt drop to zero observed for ρ at the melting temperature for $H \| c$ is replaced by a continuous decrease to zero for $H \| ab$, which could not be fitted using the dynamical scaling rules corresponding to the vortex[3] or Bose[15] glass to liquid transition, and suggested the existence of a vortex-smectic phase when cooling the vortex liquid.

In this paper we provide experimental evidence supporting the existence of a vortex smectic phase when the magnetic field is applied in the direction of the *ab* planes both in clean and twinned $YBa_2Cu_3O_{7-\delta}$ single crystals. We present results on the temperature dependence of the resistivity ρ for different directions of the Lorentz force and of the longitudinal vortex velocity correlation length, $l_\|$. The detection of $l_\|$ is done using a modification of the dc flux transformer contact configuration.[11]

The twinned and untwinned $YBa_2Cu_3O_{7-\delta}$ single crystals were grown as indicated in Ref. 11, had critical transition temperatures $T_c \simeq 92$ K and transition widths $\Delta T_c \leqslant 0.3$ K. Two crystals with typical dimensions $(1 \times 0.5 \times 0.03)$ mm^3 were selected, one with a low density of twin boundaries and one untwinned. For the analysis of the vortex velocity correlation lengths, eight contacts were made in the modified transformer configuration (see inset Fig. 1), in a second stage, these contacts were removed and the configuration sketched in Fig. 2 was used. The crystals were mounted onto

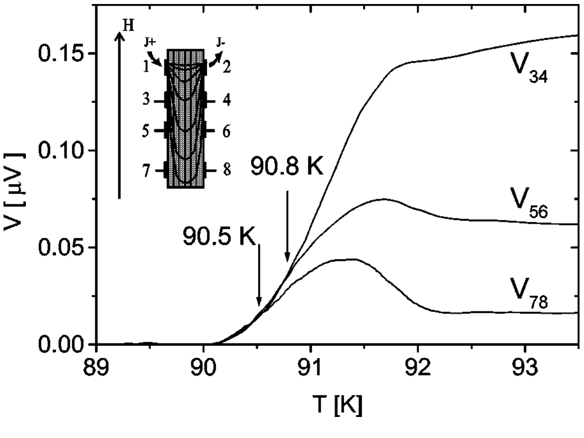

FIG. 1. Temperature dependence of the voltages V_{34}, V_{56}, and V_{78} for an applied magnetic field of 4 T parallel to the *ab* planes, and the current injected between contacts 1-2. The arrows mark the temperature at which the differences $V_{34}-V_{56}$ and $V_{34}-V_{78}$ vanish. The inset is a sketch of the electrode configuration.

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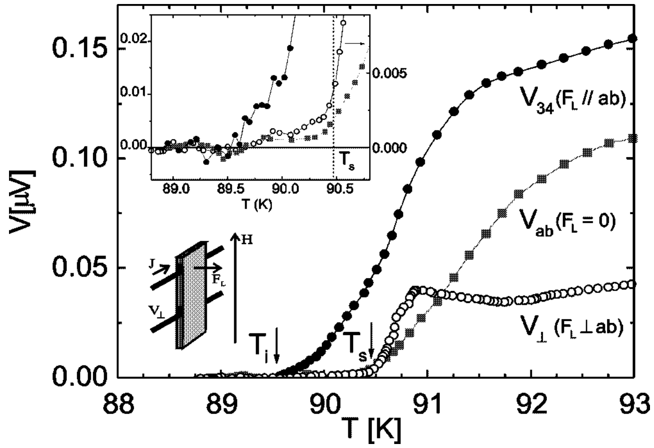

FIG. 2. Comparison between the temperature dependences of the dissipation measured with different Lorentz force configurations: solid circles (V_{34}) F_L parallel to the ab planes, gray squares (V_{ab}) $F_L=0$, and open circles ($V_\perp$) F_L perpendicular to the ab planes. The applied magnetic field is 6 T parallel to ab. The upper inset is a zoom of the low-temperature region (notice the different scales). The sketch corresponds to the electrical contact configuration used to measure $V_\perp$.

a rotatable sample holder with an angular resolution of 0.06° inside a cryostat with an 8 T magnet.

The pseudo-dc-flux transformer technique used to determine $l_\parallel$ is based on the fact that in the mixed state a voltage between a pair of contacts aligned in the current direction is associated with a flow rate of vortices between them. As shown in the inset of Fig. 1, a current is injected inhomogeneously through the sample using contacts 1-2. Therefore, the current takes different values accross each pair of voltage contacts 3-4, 5-6, and 7-8. If the magnitude of the current is small enough to avoid vortex cutting, the different forces applied at different parts of the vortex would integrate along the vortex velocity correlation length $l_\parallel$. Thus, each point of the vortex within this length will have the same velocity irrespective of the local value of the current. Consequently, any two pairs of voltage contacts will measure the same voltage drop as soon as $l_\parallel$ spans from the current contacts 1-2 down to the furthest pair where the voltage is measured. In this way, this multiterminal configuration allows us to measure $l_\parallel$ at two different temperatures, i.e., one when $V_{34}=V_{56}$ and the other when $V_{34}=V_{78}$.[16]

The longitudinal resistivity can be measured injecting the current between 1-7 and 2-8 and detecting the voltage between 3-5 or 4-6. Some remarks are appropiate when discussing the dissipation in the ''free-force'' configuration. When the current is homogeneously injected in the samples between contacts 1-7 and 2-8, and the voltage is measured between 3-5 or 4-6, no net force is applied (in the linear response limit) on vortices that in average follow the field direction. In this limit the dissipation is associated with thermally induced vortex cutting and reconnection at average distances determined by $l_\parallel$. In the liquid state, vortex crossing generates infinite ''horizontal'' vortices whose average direction is perpendicular to the applied field. When the temperature is decreased, the vortices induced by the external magnetic field parallel to the Cu-O planes tend to be localized within them. Thus two vortex correlation lengths[15] are expected to determine the elastic properties of the vortex structure: one associated with vortex crossing within the planes, and the other with out-of-plane vortex crossing. Due to the confining potential associated with the Cu-O planes the liquid will have a larger fraction of ''horizontal'' vortices within the planes than out of them. As a consequence, the vortex mobility across them will be reduced when compared with the horizontal component interconecting planes. At the expected smectic transition,[12] the dissipation should be essentially zero for the ''free-force'' configuration.

Figure 1 shows the behavior of V_{34}, V_{56}, and V_{78} voltages measured as a function of temperature for a 4 T magnetic field applied parallel to the ab planes, and the current injected between contacts 1-2. When the temperature is lowered towards T_i, where the resistivity vanishes, the voltage V_{56} becomes equal to V_{34} at a higher temperature than that where $V_{78}=V_{34}$. These results determine two temperatures, indicated in the figure, where $l_\parallel$ coincides with the distance between the current and the respective voltage contacts. That is, $l_\parallel \simeq 250$ μm between the contacts 1-2 and 5-6, and $l_\parallel \simeq 500$ μm between contacts 1-2 and 7-8. We see that the increase of the vortex correlation length in a factor of 2 takes place in only 0.3 K. This shows a rapid growth of the vortex correlation length as the temperature T_i is approached and indicates a possible continuous transition towards a solid vortex state. This behavior is found in twinned as well as in untwinned samples, showing that twin boundaries play no significant role in the physics of vortices in this field orientation.

It is interesting to note that correlation lengths of the order of a millimeter are experimentally detected, indicating the important role of the copper-oxygen planes in establishing long velocity correlation lengths along them. It should be recalled that when the field is applied parallel to the c axis, the vortex correlation length in the liquid state in untwinned samples just above the melting, is shorter than 10 μm.[17]

The results discussed above were obtained with the Lorentz force *along* the ab planes, where the vortex mobility is the largest. If the vanishing of the resistivity is determined by a phase transition in the vortex structure, the temperature at which this occurs should be independent of the direction of the applied current. On the contrary if T_i is due to the onset of a critical current induced by the intrinsic pinning it should depend on the direction the vortices move. In order to distinguish between the two possibilities we removed the contacts of one of the samples and put them as to have the Lorenz force *orthogonal* to the ab planes. This configuration is sketched in Fig. 2. The results for the voltage measured in this case, $V_\perp(T)$, (open circles) are compared in this figure with those obtained in the previous configuration (solid circles) and with the voltage V_{ab} (gray squares) measured between the contacts 3-5 in the free-force configuration for $H_\parallel = 6$ T. We have checked that all these measurements are within the linear-response regime. Although the temperature dependence and the amount of dissipation are remarkably different, the temperature at which the resistivity vanishes is the same for all configurations as shown in an expanded scale in the inset. The curve $V_\perp$ shows a sharp drop at a temperature T_s where it seems to vanish. However, below T_s a small tail develops remaining finite down to T_i (see inset). A similar behavior is seen for the longitudinal voltage V_{ab}, i.e., although the dissipation is significantly reduced at T_s it vanishes at T_i. Therefore, the dissipation for three different Lorentz force configurations becomes zero at the same temperature. We interpret this fact, together with the large value of $l_{\|}$ and its rapid increase as T_i is approached, as a signature of a continuous transition towards the solid. However, our measurements have shown the lack of Bose- or vortex-glass scaling for the *I-V* curves around T_i ruling out this type of transitions.

It is worth to mention here that in both types of samples (twinned and untwinned) T_s disappears when the field is tilted ~2° from the ab planes. The RT curves show the appearance of an abrupt first-order-like jump towards zero.[4] A discussion of the angular dependence is left for a future work.[18]

To summarize we can identify three different regions. One below T_i, where the vortex structure is a pinned solid and the resistivity is zero, another above T_s, where the vortices are in a liquid state, with high resistivity and characterized by a short vortex velocity correlation length in the field direction, and finally an intermediate region, between T_i and T_s where the dynamical response of the vortex structure shows a particular behavior. In the following we discuss the characteristics of this intermediate region within the theoretical framework developed by Balents and Nelson.[12]

In the liquid phase the tilt modulus is predicted to have a nondivergent singularity at the transition to the smectic state,[12] that is, it grows rapidly at T_s but remains finite. It is also expected[12] that the resistivity of the liquid would rapidly drop at T_s to a small but nonzero value $\rho(T_s)$ when the Lorentz force is perpendicular to the Cu-O planes. Both of these features are qualitatively seen in our data on approaching T_s: A rapid increase of the longitudinal vortex velocity correlation length, indicating the growth of the tilt modulus, and a steep descent in $V_{\perp}$. Moreover, since the transition to the smectic phase implies no change of the vortex structure in the direction parallel to the Cu-O planes, the resistivity should not show considerable changes at T_s when the Lorentz force is in this direction. Indeed in our experiments with the Lorentz force in the direction of the planes the transition to the smectic phase is evidenced only through the establishment of coherence along the field direction (see Figs. 1 and 2).

On approaching the transition to the liquid state and when the Lorentz force is perpendicular to the Cu-O planes, the resistivity is expected to increase as a power law of the form[12]

$$\rho(T)-\rho(T_s)\sim|T-T_s|^{(1-\alpha)} \tag{1}$$

where α is the specific-heat exponent. In order to see whether our data follow this behavior, we plot in Fig. 3 $|V_{\perp}(T)-V_{\perp}(T_s)|$ as a function of $|T-T_s|$ for a field of 8 T. As shown by the solid line, the data for temperatures near and below T_s are well fitted by Eq. (1) with the critical exponent $(1-\alpha)=0.4\pm0.1$ and $T_s=89.9\pm0.03$ K. The exponent is found to be field independent within the experimental error as seen in the upper inset. It is interesting to mention that calorimetric measurements in liquid crystals[19] give specific-heat exponents α for the nematic to smectic-A transition which range between 0.3 and 0.5. In the lower inset we show the region (shaded area) in the *H-T* phase diagram where a smectic phase develops.

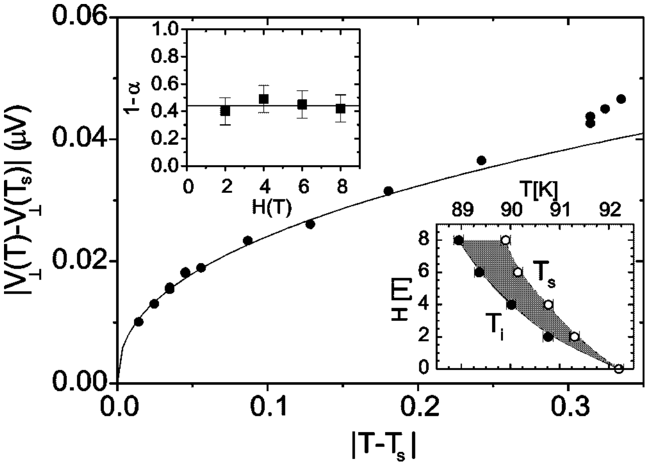

FIG. 3. Lower branch of the function $|V_{\perp}(T)-V_{\perp}(T_s)|$ versus $|T-T_s|$ for an applied magnetic field of 8 T (solid circles). The solid line is a fit according to Eq. (1). The upper inset shows the values of the exponent $(1-\alpha)$ obtained for applied magnetic fields ranging from 2 to 8 T. The lower inset is the *H-T* phase diagram.

It is puzzling that the resistivity data for temperatures above and close to T_s do not follow the expected power law given by Eq. (1) associated with the critical regime. This could be an indication of an asymmetry in the width of the critical region, i.e., a reduction of the critical range in the disordered state.

In summary we have shown that when the magnetic field is applied parallel to the ab planes, the correlation length along the field direction grows rapidly below T_s as the temperature is reduced towards T_i. Independently of the orientation of the applied current direction with respect to the planar periodic potential and the magnetic field the linear dissipation measured in the three different configurations $V(F_L\|ab)$, $V(F_L=0)$, and $V(F_L\perp ab)$ vanishes at the same temperature T_i. While $V(F_L\|ab)$ shows no distinctive feature at T_s, the other two voltages, $V(F_L=0)$ and $V(F_L\perp ab)$, drop rapidly at this temperature with a remanent small dissipation tail below it. All these features can be consistently described assuming the existence of a vortex smectic phase between T_s and T_i. In particular the dissipation below T_s is very well described assuming a nondivergent singularity for the resistivity at T_s as predicted by the theory[12] with exponent α in good coincidence with specific-heat exponents reported for smectic-nematic transitions in liquid crystals. These experimental results provide strong evidence for the existence of a thermodynamic liquid to smectic transition at T_s.

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[16] Notice that in this work the transformer contact configuration differs from that used in previous works (Ref. 11), where the vortex velocity correlation $l_{\parallel}$ is determined when it equals the thickness of the sample. The present method can also be used to measure vortex velocity correlation lengths of the isotropic low-temperature superconductors.

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