Role of Twin Boundaries on the Vortex Dynamics in $YBa_2Cu_3O_7$

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By means of a novel technique of rotating the applied current we have directly measured the influence of twin boundaries on the vortex motion in a $YBa_2Cu_3O_7$ single crystal. The results indicate that the effect of twin planes on the vortex dynamics starts to develop below a certain temperature, being responsible for an anisotropic viscosity in the vortex liquid state and a guided motion in the solid state.

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The study of vortex matter in superconductors has great interest from several points of view. Technologically it is important to control vortex mobility and consequently the dissipation produced by this motion. Statistically, it is an example of a complex system consisting of elastic objects immersed in a highly viscous media with long ranged interactions. Quenched disorder, anisotropy, and thermal fluctuations provide additional elements that contribute to the richness of the subject [1].

The effect of an oriented potential in the dynamic response of the vortex system is worth discussing. Obtaining the direction of motion is a nontrivial task, although certainly it would be affected by the presence of this kind of potential. An extreme case would be a guided vortex motion where the direction is determined by the subjacent symmetry [2,3].

In this Letter we present results of electrical transport measurements on a twin-oriented $YBa_2Cu_3O_7$ (YBCO) single crystal. In order to test the influence of twin plane boundaries on the vortex motion we have used a novel technique with four pairs of coplanar contacts which allow us to control the direction of the applied current. Two pairs were aligned as in a classical transport experiment and two other similar pairs were oriented 90° with respect to the previous ones (see sketch in Fig. 1). Using two current sources through the external contacts, we were able to rotate the current direction in the *ab* plane in a continuous way. Measuring simultaneously the voltages in both directions it is possible to extract directly the velocity and *direction* of vortex motion. This permits us to measure in the *same* crystal the transport properties along and across the twin planes and in any other orientation.

A crystal grown by the self-flux technique [4] having twin planes oriented only in one direction was selected. Crystal dimensions were 1×1.1 mm^2 in the *ab* plane and 75 μm in the c axis. Regularly spaced twins with an average separation of 5 μm were observed in the crystal by microscope inspection under polarized light. Silver pads were sputtered on one of the faces through an *ad hoc* Cu mask and gold wires were attached with silver epoxy. dc resistance measurements were performed as a function of temperature at different magnetic fields applied in the c axis using a two channel nanovoltmeter.

In Fig. 1 we show the superconducting transitions for the longitudinal and transverse voltage when the current is fed through one pair of the current contacts. In this case the applied current makes an angle of 52° with the twin planes [5]. The longitudinal component of the voltage shows the typical broadening on magnetic field and, close to the zero resistance temperature, the kink usually associated with the onset of twin boundary pinning [6]. Close to this temperature superconducting coherence is established along the whole sample thickness and in the field direction, as has been reported through pseudo-dc-flux-transformer experiments [7]. Those experiments indicate that below certain temperature, $T_{\rm th}$, the vortices behave as continuous lines. As an example, the solid arrow drawn in Fig. 1 marks the estimated $T_{\rm th}$ for a magnetic field of 1 T [8]. At high temperatures the transversal component of the voltage presents a small signal coming from a small misalignment of the contacts and the Hall resistance [9]. Upon lowering the temperature and close to the onset of twin boundary pinning, this component starts to increase reaching, in our case, one-third of the longitudinal signal. This increase in the transverse voltage did not change on reversing the magnetic field indicating that it is not related to the Hall resistance.

This is the first relevant result of the paper which indicates that the vortex motion deviates strongly from the force direction at these temperatures. The oblique motion can be attributed to vortex guidance by twin planes [3], or more generally by an anisotropic viscosity. This latter results in an effective in-plane anisotropic resistivity tensor with its principal axis (determined in this case by the twin planes direction) rotated at an arbitrary angle with respect to the current direction [10]. In this situation it is well known that the electric field and the current are not collinear [11]. More explicitly, the longitudinal and transversal components of the voltage, neglecting the hall resistance, are given by

$$V_L = (\rho_\parallel \sin^2\alpha + \rho_\perp \cos^2\alpha)|\mathbf{j}_L|,$$
$$V_T = (\rho_\perp - \rho_\parallel)\sin\alpha\cos\alpha|\mathbf{j}_L|, \quad (1)$$

where α is the angle between the current and one of the principal axes of the system, $\rho_\perp$ and $\rho_\parallel$ are the resistivity

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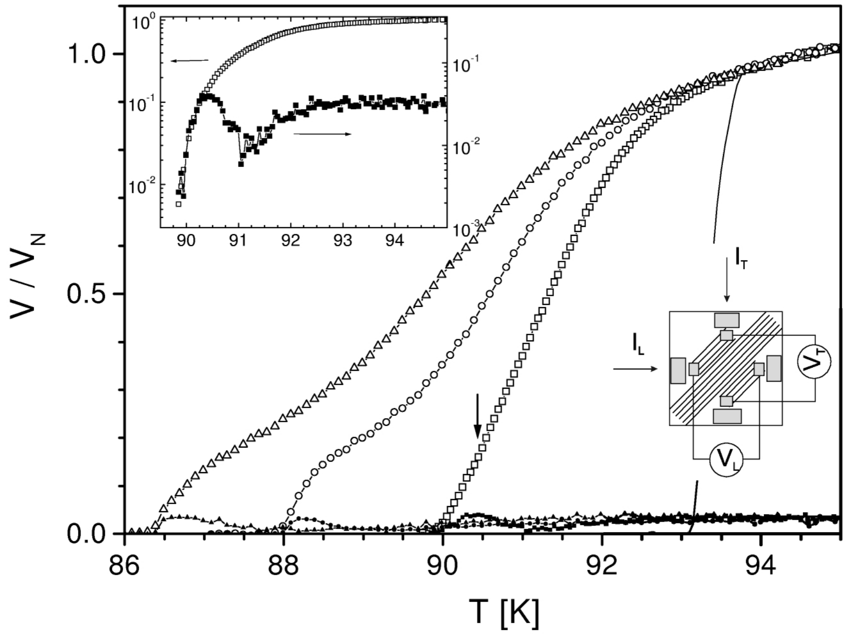

FIG. 1. Resistive transitions at different applied fields for an YBCO crystal, with unidirectional twin boundaries. The field is applied in the $c$direction and the current is applied in one of the pairs of current contacts. The open symbols correspond to the voltage measured in the same direction as the applied current, the solid ones to the voltage measured at the perpendicular direction. Solid line: zero field; squares: 1 T; circles: 2 T; triangles: 3 T. Inset: Logarithmic plot of the measurement at 1 T. The perpendicular signal was scaled by a factor of 3.

components across and along this principal axis, and $\mathbf{j}_L$ is the applied *longitudinal* current. It is important to note that this transverse voltage is *even* on reversal of the magnetic field.

Shown in the inset of Fig. 1 are the same data for the case of an applied field of 1 T with the transverse signal scaled by a factor of 3. It is clear from the data that for temperatures below 90.25 K, both signals are proportional. From Eq. (1) it can be seen that the ratio between diagonal components of the resistivity tensor must be constant in this temperature range. Furthermore, it strongly suggests that the transition to the zero resistance state in both directions occurs at the same temperature.

Guided vortex motion implies that the velocity direction of vortices keeps constant, independently of the external force. This can be tested by means of the experiment described previously: using the extra pair of current contacts, aligned at 90° (therefore collinear with the transverse voltage contacts) and by means of an additional current source, we rotate continuously the current direction maintaining the net Lorentz force constant (see sketch in Fig. 1).

In Fig. 2(a) we plot the *longitudinal* component versus the *transversal* component of the voltage when performing a current rotation for different temperatures, at an applied field of 1 T and for a constant current density of $1.25\ \mathrm{A/cm^2}$ (similar data were obtained at 2 and 3 T). As expected, for the high temperatures the data lie along a circle reflecting the behavior of an isotropic conductor where the value of the voltage response is independent of the current direction. This also can be taken as a confidence test of current homogeneity in the sample within the region of voltage contacts. On lowering the temperature and approaching the kink the data start to fall on an ellipse with its principal axis oriented along the twin planes direction. The solid line shown in the figure corresponds to a least squares fit of the data at $T = 90.25$ K using Eq. (1), showing the excellent agreement with the expected behavior of an anisotropic conductor. This elliptical response is clearly observed in the whole liquid state with coherence along the c axis [7], without any evidence of a complete vortex guidance by twin planes as was described before.

Shown in Fig. 2(b) are the data plotted as electric field angle, $\theta_E = \arctan\,(\frac{E_\parallel}{E_\perp})$, as a function of the current density angle, $\theta_j = \arctan\,(\frac{j_\parallel}{j_\perp})$, for different temperatures and with an applied magnetic field of 1 T. Again, the data are representative of the evolution from isotropic to anisotropic vortex motion. When being in the normal state as well as in the *decoupled* vortex liquid phase the electric field direction strictly follows the current direction. However, as the temperature is lowered and the in-plane anisotropy develops, the electric field angle deviates from the current angle. In Fig. 3 the exponents, $\alpha_{\parallel,\perp}$, are shown, taken from the I-V characteristics for both directions and an applied field of 1 T, as a function of temperature. Nonlinearities associated with the growth of the vortex solid phase and the development of a critical current are observed below 89.9 K. In the same graph we plot $\frac{V_\parallel - V_\perp}{V_\parallel + V_\perp}$ obtained from the current rotation experiment at different temperatures, which is as a measure of the anisotropy in the resistivity. It is evident from this figure that this anisotropy in the vortex motion starts to develop

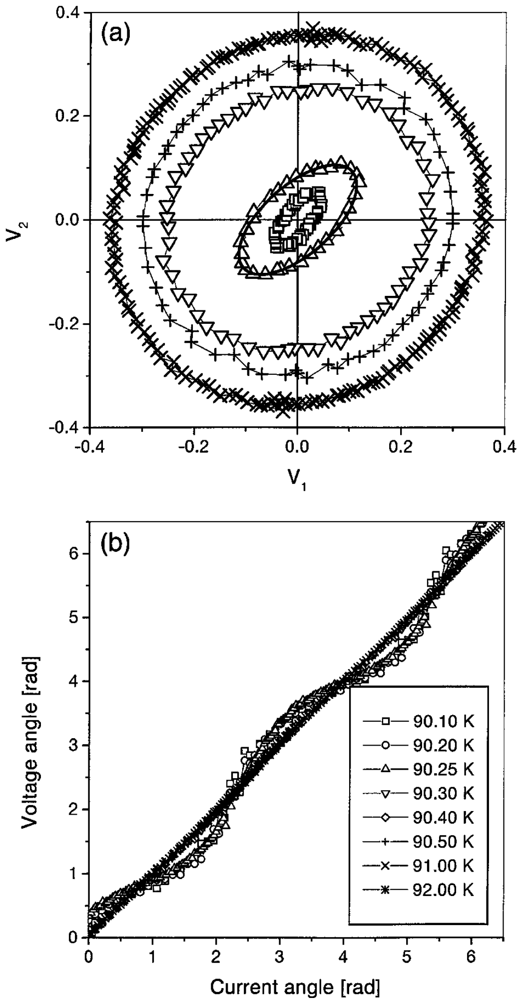

FIG. 2. (a) Longitudinal vs transversal voltage when varying the current direction at a fixed current modulus and an applied field of 1 T for different temperatures as indicated in the graph. The solid line is a least squares fitting to the data at $T = 90.25$ K. (b) Voltage angle vs the current angle at different temperatures and an applied field of 1 T.

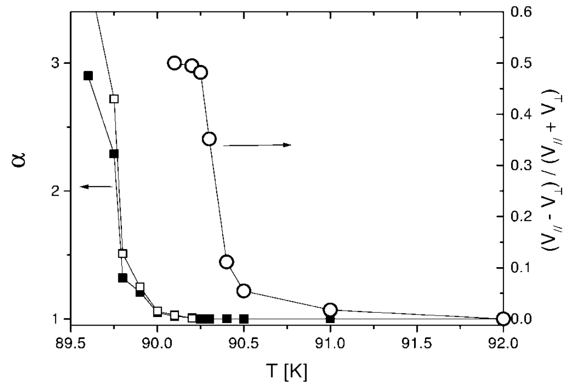

FIG. 3. Exponent taken from $V \simeq I^{\alpha}$ characteristics at different temperatures at an applied field of 1 T. Closed (open) squares: perpendicular (parallel) component. Circles: Eccentricity functional $\frac{V_{\parallel}-V_{\perp}}{V_{\parallel}+V_{\perp}}$ taken from minimum square fits of the data.

in a regime where the dynamics of vortex lines has a linear response.

Effectiveness of pinning by twin boundaries has been proved by low field magnetic decorations [12] and magneto-optical experiments [13,14] showing that there is an increase of the vortex density around twin boundaries. Although twin planes are relevant for the vortex dynamics, the present data indicate that their main effect in the vortex liquid state is to bring an anisotropic viscosity into its motion. Resistance to vortex motion arises basically from two contributions: intrinsic viscosity (or friction) associated with the drag on a single vortex (flux flow viscosity) and from vortex-vortex interaction. To explain the observed anisotropic behavior by the single vortex friction we have to include an anisotropy on the vortex characteristics, or take into account a correction to the flux flow resistivity by pinning. The first argument can be discarded because it is very unlikely that an extrinsic conditional, like the twin planes, can modify intrinsic superconducting properties starting from certain temperature. The evaluation of the effect of an oriented pinning landscape on vortex dynamics in the *linear* regime is a difficult task. In the framework of thermally activated flux flow [15] this effect is taken into account by changing the effective number of moving vortices by thermal activation over the pinning potential. The geometry of unidirectional pinning has been addressed by Mawatari [16] solving the Fokker-Planck equations which brings to an anisotropy in the resistivity. However, in this model, the ratio between resistivities could be basically expressed as $\frac{\rho_{\parallel}}{\rho_{\perp}} = \exp(\frac{U_{\perp}-U_{\parallel}}{k_B T})$. The observed temperature independence of this quantity in our data would imply that twin planes pinning has a linear temperature dependence extrapolating to zero at zero temperature.

Other explanations trying to include modifications on the pinning landscape by the external current like flux creep, necessarily end in a nonlinear behavior, in contradiction to the experimental data. In a recent paper López and co-workers [17] have observed a similar effect on crystals with *splayed* columnar defects. In their work they explain the experimentally observed anisotropy in the liquid taking into account a time t_{pl}, during which the vortices resemble the solid phase. As a consequence of the splayed defect configuration the solid phase has anisotropic elastic constants that differentiate the responses in both directions.

The reported results indicate an anisotropic dissipation below $T_{\rm th}$. This can be achieved if we suppose that at $T_{\rm th}$, and below, pinning by the twin planes becomes a center of nucleation of the entire vortex lines. At the currents used in the experiments, these vortices remain strongly pinned in the defects, generating a set of parallel irregular *grids* that the vortex liquid has to cross when the force is oriented perpendicular to the twin planes. Viscosity due to vortex entanglement is responsible for the fact that the diffusionlike motion of vortices results are different across and along these *grids*. The density of vortices pinned in the twins depends only on the density of these defects and does not depend either on temperature or on current. This

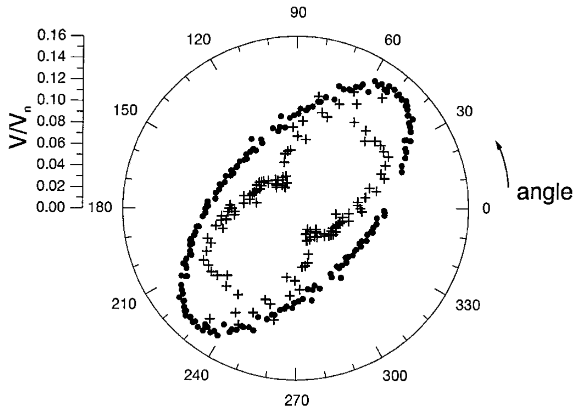

FIG. 4. Polar graph of the voltage at different temperatures for an applied field of 1 T when rotating the current direction. Circles: $T = 90.25$ K and a current density of 1.25 A/cm^2. Crosses: $T = 89.5$ K and a current density of 19 A/cm^2.

implies a saturated regime in which the applied current is sufficiently below the critical current of the strongly pinned vortices. Under these circumstances the relation between resistivities would remain constant as a function of the temperature, as observed.

Different and striking features are observed in the solid vortex phase. In Fig. 4 we plot the data obtained in the rotating current experiment for an applied field of 1 T at 89.5 K with a current density of 19 A/cm^2, higher than the critical current density in both directions. For comparison, the 90.25 K data taken with a current density of 1.25 A/cm^2 are shown in the same graph. From this figure it is clear that different mechanisms are involved in the vortex motion. The elliptical shape evolves towards a squared eight-shaped curve, with a marked minimum for the direction normal to the twin planes. Looking at the vortex velocity across twins, the data show a minimum in the motion when the force is maximum along that direction. This component of velocity starts to increase as soon as the velocity increases, reaching an almost constant value. Following the previous scenario, twin pinned vortices act like a sieve for the others which are now condensed in a solid phase. To move across twin planes vortices have to be able to explore laterally in order to find weak channels to go through. In the liquid phase the lateral displacement is occurring naturally because of the lack of shear modulus. On the other hand, the same displacement in the solid, with a finite shear stress capability [18,19], is allowed only when it is externally forced to move sideways. Therefore, the experimental data support the existence of a guided motion along twin planes, with a constant component of velocity in the perpendicular direction.

In summary, we have presented experimental data in a twin oriented crystal that indicate an anisotropic vortex motion on a field dependent temperature range. This anisotropy is different in the solid than in the liquid phase. In the former there is evidence for a guided motion along the twins, whereas in the liquid the response is consistent with an anisotropic vortex viscosity.

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