Experimental evidence for vortex lines in the vortex-liquid phase of $YBa_2Cu_3O_{6.95}$ in a geometry of tilted vortices

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Using a transport method with a geometry of tilted magnetic field, we have studied the direction of the electric field generated by the motion of vortices. This experiment gives evidence of uncut vortex lines in slightly overdoped untwinned $YBa_2Cu_3O_{6.95}$ above the melting first order transition, showing that the first order transition does not correspond to a decoupling of the vortex lines. The gradual loss of the line correlation appears close to T_{c2} on a width which is typically that of the critical fluctuations. Those results are similar to what we have found previously in a heavily twinned sample and lead to the conclusion that the twin planes are not necessary to induce uncut vortex lines in the liquid phase, even in a thick sample. Moreover, we observe a nonzero transverse voltage below the critical current, which is not explained unless referring to surface nondissipative currents. [S0163-1829(99)10201-7]

INTRODUCTION

In high-T_c superconductors, strong thermal fluctuations and large anisotropy are responsible for new aspects of the vortex behavior.[1–3] In particular, it has been experimentally shown that the aspect of the transition under magnetic field is dependent of the type of disorder. In clean and untwinned optimally doped YBaCuO, it is considered as a first order transition (the so called melting transition) while the field is not too high.[4,5] It may be suppressed by disorder such as twin boundaries or columnar defects. In heavily twinned YBaCuO, the transition is continuous.[6] Many questions remain about the nature and behavior of the vortices in the liquid phase above these transitions. It is still unclear if the vortices can be considered as uncut vortex lines, as in the mixed state of an ideal type-II superconductor, or if the melting is accompanied by the loss of vortex line coherence, resulting from a decoupling in individual pancakes or from the possibility for the vortex lines to cut and reconnect.[7–9]

In order to study this loss of line correlation, it was proposed to use the ''flux-transformer geometry.''[10,11] With this configuration, it was shown that in YBaCuO with twin boundaries[12] or with columnar defects,[13] the vortices are still correlated above the irreversibility line. The same experiment in untwinned YBaCuO has led to the conclusion that no more correlation exists in the absence of such extended defects.[14] Recently, short range correlations were observed in thin samples by the same technique.[15]

We have chosen another configuration described by Mathieu *et al.*[16] The geometry is explained in Fig. 1. The magnetic field makes an angle θ_B with the c axis. Measuring V_x and V_z, we are able to extract $\theta_E = \tan^{-1}(V_z d/V_x e)$ which defines the direction of the electric field generated by the motion of vortices (e and d are the distances between the contacts defined in Fig. 1). In the mixed state of an ideal type-II superconductor, the regime of dissipation is the flux-flow regime, the Josephson relation $\mathbf{E} = -\mathbf{v}_1 \wedge \mathbf{B}$ can be applied and $\theta_B = \theta_E$ up to H_{c2} [an experimental verification is in reference in Pb-In (10%) (Ref. 16)]. In the case of uncorrelated pancakes moving in the plane, the electric field is also in the plane. The existence of a transverse voltage in this geometry is the signature of some correlations and $\theta_B = \theta_E$ that of the existence of uncut vortex lines. In low T_c's, the jump of θ_E and θ_B to 0 at $Bc2$ is very sharp. Such an experiment has already allowed to show in a twinned YBaCuO sample that the situation is very similar, with a progressive decrease of θ_E at H_{c2} (Ref. 17) over a width which is typically that of the critical fluctuations. As a consequence, there the two extremities of the flux lines are moving at the same speed, even above this line. The main difference with the

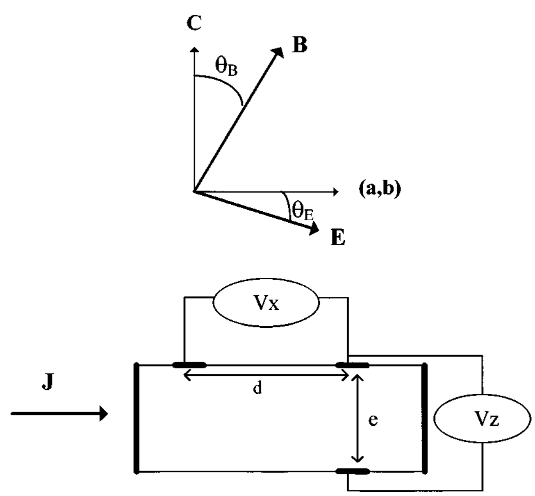

FIG. 1. The geometry used for this experiment. The current is injected through the lateral faces, to achieve a homogeneous distribution with J parallel to the $(\mathbf{a},\mathbf{b})$ plane. The magnetic field makes an angle θ_B with the c axis. With a dissipation flux flow, the electric field generated by the motion of vortices makes the same angle with the $(\mathbf{a},\mathbf{b})$ plane. The direction of this field is experimentally given by $\theta_E = \tan^{-1}(E_z/E_x)$.

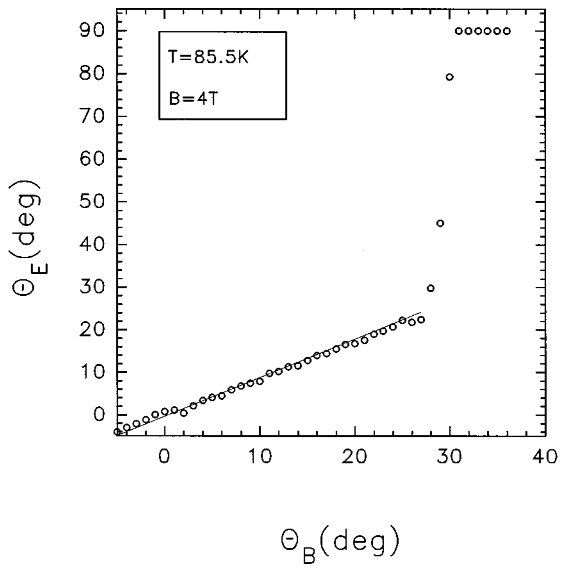

FIG. 2. θ_E as function of θ_B for $I=10$ mA, $B=4$ T, and $T=85.5$ K. The variation is linear up to the transition shown by the straight augmentation of θ_E (the line is a guide for the eyes).

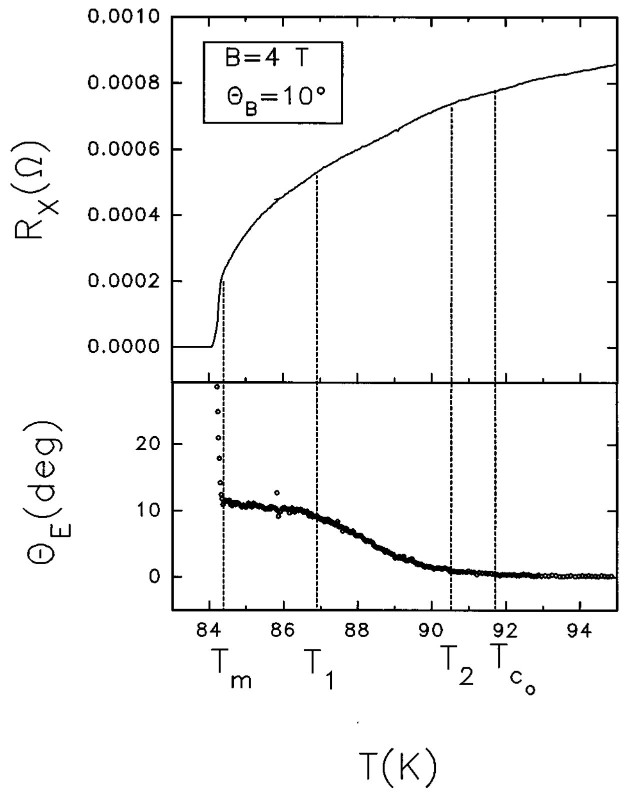

FIG. 3. On the same figure, θ_E and R_x as function of T for $B=4$ T, $\theta_B=10°$, and $I=10$ mA. $\theta_E \approx \theta_B$ at low temperature provides evidence of a line comportment for the vortices above T_m. Two other characteristic temperatures are shown. They are limiting respectively the line behavior (up to T_1), a progressive decorrelation (up to T_2) and a state where no more transversal coherence exits (above T_2). Below T_m, θ_E increases as the temperature decreases to reach 90°.

flux transformer geometry is the absence of any shear force due to the current if it is homogeneous in the sample.

We have performed here the same experiment in an untwinned crystal of YBaCuO. In such a sample with a small density of extended defects compared to the vortex density, we will be able to see if the vortex phase coherence is still preserved. On the contrary, if the vortex lines in the liquid phase can cut and reconnect over a length scale which is smaller than the sample thickness, the angle θ_E should start to decrease at the first order transition.

EXPERIMENTAL

The sample is an $YBa_2Cu_3O_{7-\delta}$ crystal of length: 4.5×thickness 1×width 0.5 mm^3. We chose the slightly overdoped regime to have a high T_c and to avoid large amount of oxygen disorder. The details of the sample preparation were previously given.[18] The sample was annealed at 480 °C for 48 h. It is then obtained nearly optimally doped with a melting line indicating the first order transition up to more than 7 T. This was verified by observing sharp jumps in magnetization in the SQUID technique. The experimental value of T_c and the annealing conditions coincide with slight overdoping (1 K) of a high purity sample. A few twinning stripes of nanosize thickness were detected with polarized light in the bulk untwinned matrix. The density of such mince stripes is certainly few orders of magnitude smaller than the vortex density at the 4 T that we have chosen here.

Gold wires were attached to silver pads. The resistance contacts were so typically less than 1 Ω. The distances between the contacts are $e=1$ mm and $d=2.5$ mm. The cryostat is a home made setup (see Ref. 19 for more details). To be sure that any misalignment of the contacts does not perturb the results, we have for each measure performed θ_B and his symmetric with respect to the current vector. This procedure eliminates a possible contribution of V_x or V_z.

RESULTS AND DISCUSSION

Figure 2 shows θ_E as function of θ_B at $T=85.5$ K and $B=4$ T, i.e., in the liquid phase above the first order transition. The variation is linear with $\theta_B \approx \theta_E$ which is consistent with uncut vortex lines. This was found at many different magnetic fields up to 6 T. This is direct proof of the continuous nature of the vortex lines in the liquid phase over a length which is larger than the sample width (1 mm). Note that the flux transformer geometry is difficult to use with such thick samples. The presence of a large amount of twin boundaries is not necessary to prevent any vortex cutting in the liquid phase. The presence of possible few residual twins in our sample is rather similar to the existence of sample edges since the distance among them is about 100 μm. Since it is well known that the edges of the samples are very important to maintain the vortex lines straight in soft low T_c's, this should be also studied here with more detail.

At an angle corresponding to the first order transition, the longitudinal voltage V_x disappears, allowing a nonzero transverse voltage, which induces an angle of 90°. The situation in the solid phase (above 28° here) is very surprising. Note that the situation of completely uncoupled pancakes should give $\theta_E=0$. In Fig. 3 (bottom part), θ_E is represented as a function of temperature for $B=4$ T and for $\theta_B=10°$. Above the first order transition which can be seen at $T=84.25$ K on the $R_x(T)$ curve presented in the upper part of Fig. 3, we

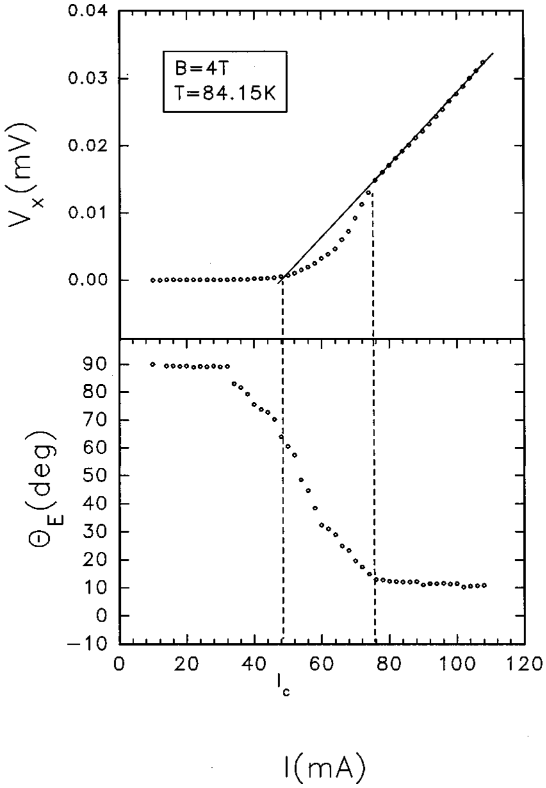

FIG. 4. V_x and θ_E as function of I for $B=4$ T, $T=84.25$ K, and $\theta_B=10°$. At high current, the regime is flux flow (the linear variation of V_x, with a slope near R_{ff}, coincides well with the saturation of θ_E at 10°). For I lower than the critical current, defined as I_c on the figure, the transverse voltage is surprisingly nonzero, resulting in the θ_E saturation at 90°.

observe that θ_E is rather constant with a value of $\theta_B=10°$. When the temperature increases and reaches the B_{c2} line, θ_E decreases progressively to zero. On the figure, we have defined two temperatures T_1 and T_2 corresponding, respectively, to 0.9_{θ_B} and 0.1_{θ_B}. The line behavior is gradually lost between T_1 and T_2 above which no more phase coherence exists ($\theta_E \approx 0°$ in the normal state).

The loss of the coherence which appears between T_1 and T_2 is very similar to which was already analyzed in the previous report on the twinned sample.[17] The loss of line coupling appears at about B_{c2} over a width which is typically that of the critical fluctuations. For example, at 4 T (Fig. 2), T_{co}-$T(Bc2)$ is about 2.2 K [$|dBc2/dT| \approx 1.9$ T/K (Ref. 20)] and the width of three dimensional critical fluctuations is about 4 K.[20]

In order to study the nature of the dissipation in the flux flow regime, we have studied V_x as a function of the applied current I near the ''melting'' temperature T_m at $B=4$ T and $\theta_B=10°$ (Fig. 4). At high current (corresponding with the regime where $\theta_E=\theta_B$), we have $V_x=R_{ff}(I\text{-}I_c)$. Close to I_c, the presence of the first order transition makes the curve very different from the one observed in a low T_c material. However, in a simple model of flux flow,

$$R_{ff}=R_n(T)B/B_{c2}(T). \tag{1}$$

Due to the relatively small value of θ_B, as first good approximation, we have $B_{c2}(\theta_B=10°) \approx B_{c2}(\theta_B=0°)$. We use the linearized Ginzburg-Landau equation

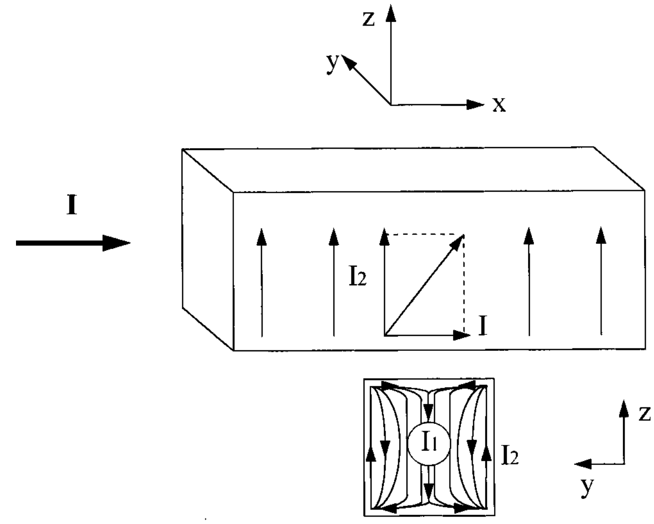

FIG. 5. The current distribution expected when V_x is zero and V_z nonzero. Only the bulk current I_1 is responsible to dissipation, while I_2 is nondissipative. The current in the direction of the transport current is superficial and nondissipative while $I<I_c$.

$$B_{c2}(T)=\Phi_0(1-T/T_c)/(2\pi\xi_{ab}^2) \tag{2}$$

with $\xi_{ab}=20$ Å and $T_{co}=91.8$ K (the experimental value). At $T=84.25$ K, the numerical application gives $R_{ff}=4.9\times10^{-4}$ Ω and is a good agreement with the experimental value (5.2×10^{-4} Ω).

Below the critical current I_c, the longitudinal voltage is zero, but again, there exists a transverse nonzero component ($\theta_E=90°$). The consistency of this observation ($V_x=0$; $V_z\neq0$) in different experimental situations suggests that this is a real physical effect. We find no interpretation if we assume that the transport current is a bulk and homogeneous current below I_c. The absence of vortex lines should give $\theta_E=0$ instead of 90°.

As explanation can be found using a model proposed by Mathieu *et al.*[16] which predicts this effect for soft type-II superconductors. The principle of this model is that the nondissipative transport current I below I_c is superficial and changes its direction in order to maintain a zero dissipation, i.e., $V_x=0$ (in Fig. 5, a I_2 component appears). The anisotropy of the critical current I_c can allow for this. However, any directional deviation of I in the z direction (I_2) must be compensated by a component in the opposite z direction (I_1 in Fig. 5) since the current cannot flow out of the sample if there are no current leads. The interesting part here is that if the nature of the two components differs, i.e., one is nondissipative and superficial (I_2) and the other is in the bulk and dissipative (I_1), we will observe $I_z=I_1+I_2=0$ but $V_z\neq0$, as seen in the above experiments. The details of this model are described in Ref. 16.

In this type of a model, an overall dissipative bulk current is observed when all of the superficial, nondissipative current paths are exhausted at $I=I_c$, and then the vortex motion occurs.[21] This is consistent with our present observation. Above the irreversibility line, $I_c=0$ and there are no more superficial currents, so the current is indeed homogeneous in the sample when the decoupling of the vortex lines occur at

B_{c2}. Many other consequences of this model can be also experimentally verified and this will be the subject of future works.

CONCLUSION

This experiment shows the line behavior of the vortices in the dissipative regime of an untwinned YBaCuO sample which presents a first order transition. Above the critical current, the dissipation is similar to that of a moving crystal of vortices with the resistivity of the flux flow regime. Close to H_{c2}, the line correlation is gradually lost. Below the critical current, it appears a transverse voltage in a region where the longitudinal one is zero (not dissipative regime). This unusual phenomenon can be qualitatively explained if we consider the change of the current distribution at the ''melting transition,'' and if we separate the transport current in two components, as predicted by the Mathieu-Simon theory.

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