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Dynamic softening of vortex lines in $YBa_2Cu_3O_{7-\delta}$ single crystals

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Abstract

Transport measurements in the mixed state of oxygen-deficient $YBa_2Cu_3O_{7-\delta}$ single crystals using the flux transformer configuration show that the flux liquid changes with increasing anisotropy from strongly correlated to uncorrelated in the field direction. For intermediate coupling, the current inducing loss of vortex correlation has a maximum near the irreversibility temperature. Thus, an effective softening of vortex lines with decreasing temperature is detected. We propose a simple model that accounts for this behavior by including the effects of the pinning potential on the dynamics of vortices.

After extensive experimental and theoretical work the importance is now well established of disorder in the static and dynamic properties of the mixed state of high-temperature superconductors. The disorder induced by thermal fluctuations is responsible for the existence of a large region in the H–T (magnetic field–temperature) phase diagram where the vortex system is a fluid [1,2]. Reducing the temperature, this vortex liquid transforms into a vortex solid [1,3] at the irreversibility temperature $T_i(H)$. The effects of static disorder are more subtle. The critical point of the melting transition in $YBa_2Cu_3O_7$ (YBCO) changes with disorder and the first-order transition from a liquid to a crystalline solid is suppressed for strong enough disorder [4]. In this case, the vortex liquid transforms into a vortex glass through a second-order phase transition [5]. The influence of disorder on the recently discovered first-order transition [3] in the more anisotropic $Bi_2Sr_2CaCu_2O_8$ (BSCCO) has not been studied yet. However, the static disorder induced by defects causes [6] the irreversible behavior [7] of the critical current in the c direction in BSCCO single crystals. The results in YBCO as well as in BSCCO provide experimental evidence that defects play an important role in determining the equilibrium properties of the vortex structure.

Although, as discussed above, disorder influences the superconducting response of both the moderately anisotropic YBCO and the weakly coupled BSCCO, the temperature region where the vortex lattice changes from three- to two-dimensional behavior is

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quite different, depending on the anisotropy. In the case of YBCO it has been shown [8] that a liquid of vortex lines exists above $T_i(H)$. These lines lose their superconducting correlation along the c direction at a temperature $T_{th}(H) > T_i(H)$. On the other hand, in the case of BSCCO the vortex correlation in the c direction in the vortex-glass structure is lost [3] at temperatures $T_{th}(H) < T_i(H)$. Therefore, two-dimensional vortices undergo the solid–liquid transition in BSCCO while three-dimensional vortex lines transform to a liquid in YBCO. Important questions such as how this decoupling process changes with anisotropy and how it is influenced by disorder, remain unsolved.

In order to shed light on this issue we decided to investigate the dynamic properties of the flux lines when the strength of the coupling between the CuO planes is varied. Using the so called DC flux transformer configuration it is possible to determine the conditions under which the vortex correlation across the sample is destroyed [8]. Since oxygen deficiency increases the anisotropy of YBCO [9], we used this technique in single crystals with controlled oxygen stoichiometries to follow the influence that anisotropy and disorder have on the decoupling process in high-T_c materials.

In this paper we show that for intermediate coupling between the CuO planes there is a temperature range in which temperature *increases* the stiffness of vortices, suggesting that, in this regime, the elastic properties of the flux-line lattice are determined by the interplay between quenched disorder and thermal fluctuations. Besides, using a simple extension of the models of Refs. [10] and [11] for the DC flux transformer, we give a qualitative explanation of the experimental results, providing an insight into the possible mechanism by which the combination of pinning potential and thermal fluctuations determine the stiffness of vortices.

Oxygen-deficient $YBa_2Cu_3O_{7-\delta}$ single crystals were prepared in a controlled way using a method developed for thin-film samples [12]. This method is based on the oxygen partial pressure–temperature phase diagram [13] and allows the production of highly reproducible YBCO oxygen-deficient samples with $0\ K < T_c < 93\ K$ and small transition widths ($\Delta T_c \lesssim 1$ K). Electrical contacts with resistances between 1 Ω and 5 Ω were made by evaporating gold

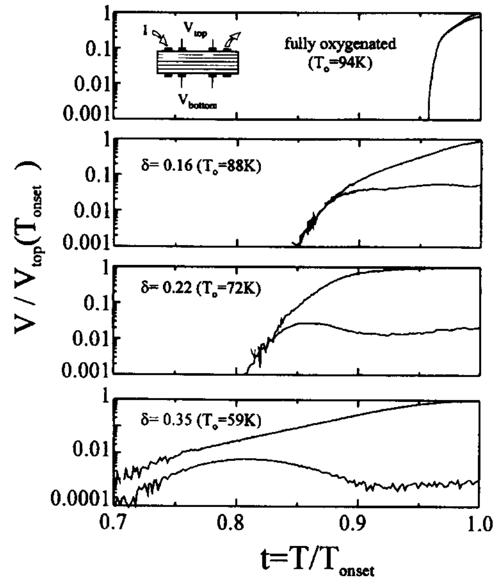

Fig. 1. Measured temperature dependences of the top and bottom normalized voltages of $YBa_2Cu_3O_{7-\delta}$ single crystals with different oxygen content in an applied field of 10 kOe parallel to the c-axis. The data shown in the two upper panels correspond to the same sample. Inset: sketch of the electrode configuration.

before deoxygenation, following the procedure described in Ref. [8]. After deoxygenation gold wires were attached to each contact pad with silver epoxy and heat treated in air at 50°C for 8–10 h.

Shown in Fig. 1 are the top and bottom voltages, V_{top} and V_{bottom} (see inset Fig. 1), normalized by V_{top} at the zero-field onset temperature, T_0, as a function of the reduced temperature, $t = T/T_0$ (for details of the experimental setup see Ref. [8]). The magnetic field is 10 kOe applied parallel to the c-axis. The data correspond to crystals with oxygen contents ranging from nearly stoichiometric ($T_0 = 94$ K, upper panel) to $\delta \simeq 0.35$ ($T_0 = 59$ K, lower panel). Sample dimensions are typically $(0.8 \times 0.5)\ mm^2$ in the ab planes and 0.03 to 0.04 mm in the c direction. All curves have been taken within the linear-response regime. Several features of the data show a systematic variation with decreasing oxygen content [14]. It is clearly seen that in the normal state, $t \geq 1$, the ratio V_{top}/V_{bottom} increases when δ is increased. For example, at $t = 1$, the ratio V_{top}/V_{bottom} increases from 1.2 for the $T_0 = 94$ K sample (see also Ref. [8]) to about 1200 for the oxygen-deficient crystal with $T_0 = 59$ K. This result is in agreement with the expected increases of the ratio between the c-axis and in-plane resistivities, ρ_c/ρ_{ab} [15]. In the samples with $\delta \leq 0.22$, as the temperature is lowered V_{top} approaches V_{bottom}, and the two voltages become equal (within the experimental accuracy of 20 nV) for $T \leq T_{th}$. It is also evident that when the oxygen content is lowered, $t_{th} = T_{th}/T_0$ moves towards lower reduced temperatures, indicating that the increase in anisotropy diminishes the strength of the coupling between vortices in adjacent layers. This is confirmed by the result for larger values of the anisotropy ($\delta = 0.35$), showing that V_{top} remains greater than V_{bottom} over the entire temperature range, indicating that vortex cutting and recombination dominates the superconducting response. This behavior, namely the absence of coherent vortex lines above $T_i(H)$, is similar to that observed in BSCCO using the same contact configuration [16]. Therefore, there exists a certain value δ^* ($\delta^* \sim 0.30 \pm 0.05$) separating two different regimes: for $\delta < \delta^*$ there is a range of temperature and magnetic field where vortices form a liquid of correlated lines; for $\delta > \delta^*$ the vortex liquid shows no correlation in the c direction above $T_i(H)$.

In order to investigate the interplay between disorder and anisotropy, V_{top} and V_{bottom} were measured as a function of current for samples with different oxygen contents. In the case of fully oxygenated YBCO it was found [10] that the current that induces flux cutting, I_{cut}, is independent of the presence of pinning. In Fig. 2 we show the flux cutting current, I_{cut}, and the critical current, I_{cr}, as a function of temperature for a fully oxygenated crystal (Fig. 2(a)) and for the same sample after deoxygenation ($\delta = 0.16$) (Fig. 2(b)). The cutting current is defined [8] as the current where V_{top} starts to differ from V_{bottom} (see inset Fig. 2(a)) and I_{cr} as the current for which the voltage exceeds 20 nV. These data were obtained for an applied field of 10 kOe parallel to the c-axis. For the fully oxygenated crystal the linear temperature dependence of I_{cut} above and below $T_i(H)$ was explained [10], arguing that pinning does not affect the vortex correlation length in the field direction for $I > I_{cr}$. In contrast, Fig. 2(b) shows that for the more anisotropic sample, I_{cut} displays a non-monotonic behavior as a function of temperature. Below T_{th}, I_{cut} increases linearly with decreasing temperature and close to the irreversibility temperature it begins to

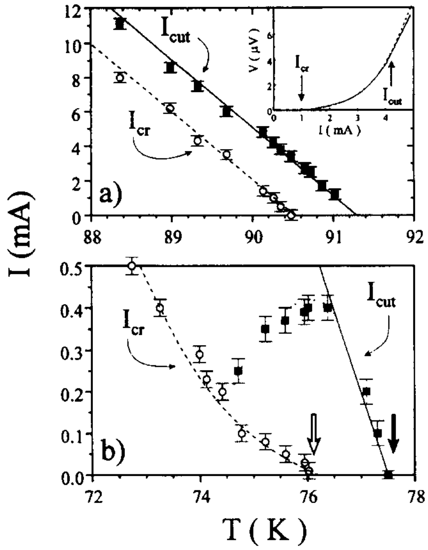

Fig. 2. Shown are the critical and cutting currents, I_{cr} and I_{cut} respectively, as a function of temperature for $H = 10$ kOe parallel to the c-axis. (a) Fully oxygenated crystal. Inset: typical $I-V$ characteristic showing I_{cr} and I_{cut}. (b) The same sample as in (a) after deoxygenation ($\delta = 0.16$). Open and solid arrows mark the temperatures T_i and T_{th}, respectively.

decrease. We observed the same non-monotonic behavior for other oxygen deficiencies and for different applied magnetic fields. A straightforward implication of these data is that the vortex lines effectively *soften* with *decreasing* temperature for temperatures close to $T_i(H)$. This striking behavior of $I_{cut}(T)$ is a novel feature and suggests that with increased anisotropy the elastic properties of the vortex structure are indeed sensitive to the static disorder.

A qualitative explanation of this non-monotonic behavior can be given in terms of a simple model which describes the dynamics of the vortices in these layered superconductors [10,11].

Originally Ekin et al. [11] proposed a model to describe the DC flux transformer which accounts for the interrelation between I_{cr} and I_{cut} for fully oxygenated YBCO [10]. In this theory, a vortex line is described by a single coordinate on each plane x_i (where $i = 1$ to N labels the planes in the c direction). The elastic force F_{el} connects nearest planes, and is taken as $F_{el}^{i,i+1} = a(x_{i+1} - x_i)$, where the coupling a characterizes the rigidity of the vortex. In addition, an external current I is applied on the $i = 1$ layer. The equations of the model are (for simplicity we consider hereafter only two adjacent planes):

$$\eta \partial x_1/\partial t = a(x_2 - x_1) - F_p^1 + \gamma I,$$
$$\eta \partial x_2/\partial t = -a(x_2 - x_1) - F_p^2, \qquad (1)$$

where η is an effective viscosity coefficient, F_p^i is the pinning force acting on plane i, and the last term in the first equation is the Lorentz force. In Ekin's and related models [10], $F_p^i = F_p$ is taken as a constant, and its effect is to prevent the motion of the vortex when the force acting on it is less than the value of F_p. In these works, both F_p and a are taken temperature dependent. Ekin's solution of Eqs. (1) yields $I_{cr} = 2F_p/\gamma$, and $I_{cut} = 2a\Delta x_{crit}/\gamma$, where Δx_{crit} is the value of $(x_1 - x_2)$ at which the vortex cuts and reconnects with the next one. The value Δx_{crit} is related to the vortex lattice parameter. Note that in this picture, I_{cr} and I_{cut} are determined by the pinning force and the rigidity, respectively. In order to qualitatively understand the maximum in I_{cut} versus T for the deoxygenated samples (Fig. 2(b)), we now generalize the previous model by looking in more detail into the effect of the pinning force.

We turn now to Eqs. (1) with temperature-independent parameters. We assume that the pinning potential on each plane is due to randomly distributed pinning centers. The pinning is characterized by the pinning energy, V, the range of the pinning potential, α, and the mean distance between pinning centers, d. We further consider a dilute limit, i.e., $d \gg \alpha$.

Let us first consider the motion of a vortex in this pinning potential including thermal fluctuations and the action of an homogeneous current and take the motion to be one-dimensional. The resistivity ρ as a function of temperature is found by applying the Ambegaokar–Halperin [17] result to the actual form of our pinning potential. It turns out to be

$$\rho(T)/\rho(T \to \infty) = \frac{1}{1 + \frac{\alpha}{d}\exp(V/k_B T)}. \qquad (2)$$

There are three distinct regimes (see the inset in Fig. 3). When $\rho(T)/\rho(T \to \infty) < 0.01$ the vortex is essentially trapped in a pinning center. This corresponds to the temperature range $T \lesssim V/[k_B \ln(100d/\alpha)]$. For higher temperatures the particle moves with a finite velocity. We identify $T_i(H) \simeq V/[k_B \ln(100d/\alpha)]$ as the temperature at which appreciable dissipation begins. For $T \gtrsim T_i(H)$ there are two regimes: for high temperatures – more precisely for $T \gg T^* \equiv V/[k_B \ln(0.1d/\alpha)]$ – the motion is not affected by the pinning centers, and the velocity is proportional to the applied force (flux flow). For temperatures $T_i(H) \leq T \leq T^*$ the vortex spends a finite fraction of time in pinning centers, but from time to time it is thermally depinned and dissipates until it is trapped in another pinning center. In this temperature interval the motion of the vortices is characterized by large fluctuations in the velocity. As the temperature increases the effect of the pinning centers decreases, so that T^* is a crossover temperature into the flux-flow regime.

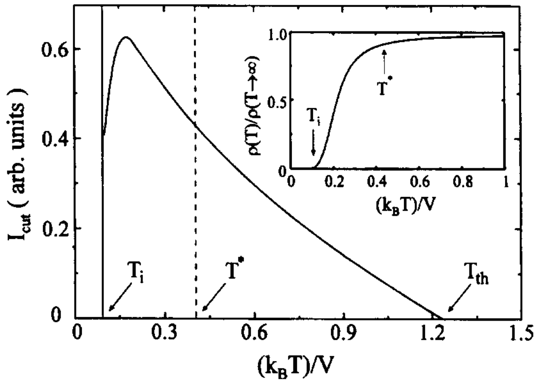

Fig. 3. Flux-cutting current I_{cut} as a function of temperature for the two-plane model described in the text. Inset: Resistivity of a single plane as a function of temperature for the same parameters. These are $d/\alpha = 100$, $(a/V)^{1/2}\Delta x_{crit} = 1$, $\tau_0 a/\eta = 10^{-3}$ and $d/\Delta x_{crit} = 1$.

The behavior of I_{cut} versus T in a DC flux transformer configuration with weakly coupled planes depends on whether T is larger or smaller than T^*. For $T \leq T_i(H)$ the vortex is pinned, and the dissipation is negligible. For $T \geq T^*$ the motion is not affected by the pinning centers and the cutting current (for which $(x_2 - x_1) \simeq \Delta x_{crit}$) goes linearly to zero at $T = T_{th}$ [10]. We consider now the intermediate temperature regime $T_i(H) \leq T \leq T^*$. When the vortex encounters a pinning center in the bottom plane, it will be trapped at that position a time τ that is roughly given by $\tau_0 \exp(V/k_B T)$, where $1/\tau_0$ is the attempt frequency. During this time interval, $\Delta x = x_1 - x_2$ increases due to the Lorentz force acting on the top plane. Clearly, if at a time smaller than τ, Δx becomes larger than Δx_{crit}, the vortex is cut. In general the effect of the pinning centers in this temperature range is to make $\langle \Delta x^2 \rangle$ greater than the thermal value without pinning. These fluctuations in the vortex deformation contribute to the cutting process. We define $P(\Delta x)$ as the probability distribution of Δx. The cutting current $I_{cut}(T)$ can be obtained as the current at which

$$\int_{\Delta x_{crit}}^{\infty} P(x)\, dx = \sigma, \qquad (3)$$

where σ is a parameter that satisfies $\sigma \ll 1$. We estimate the probability distribution $P(x)$ as the convolution of the Gaussian thermal distribution with the probability distribution due to pinning. The cutting current is obtained by solving Eq. (3) with $\sigma = 0.1$. In Fig. 3 we show a plot of $I_{cut}(T)$, where a maximum is observed within the range $T_i(H) \leq T \leq T^*$. We stress that a numerical simulation of Eq. (1) where temperature is included as a Langevin noise and the pinning potential has the spatial structure discussed above, gives results similar to that of Fig. 3. The model predicts a maximum in $I_{cut}(T)$ only for intermediate values of the coupling a. When a is too small the thermal energy masks the peak in $I_{cut}(T)$, T_{th} is reduced and eventually becomes lower than T_i. When a is too high the maximum shifts towards the $I_{cr}(T)$ curve and is unlikely to be seen in the experiments. Although the model is very simple and gives only a qualitative description of the observed behavior, it contains what we believe is the essential physics of the problem: close to $T_i(H)$, the *decreasing* temperature *increases* the fluctuations of the vortex deformation, producing an effect equivalent to a *softening* of the vortex lines.

In conclusion, our transport measurements in oxygen-deficient $YBa_2Cu_3O_{7-\delta}$ single crystals using the DC flux transformer configuration show that the dynamic behavior of the vortex structure can be strongly modified by changing the coupling between CuO planes. In samples of low anisotropy ($\delta < \delta^*$) we observe correlated vortex motion above $T_i(H)$. As the interlayer coupling decreases ($\delta > \delta^*$), the vortex liquid shows no correlation in the field direction. For intermediate coupling strengths the current I_{cut} necessary to induce the loss of vortex correlation in the field direction increases with temperature near the irreversibility line. This means that the combined effects of thermal fluctuations and the pinning potential give rise to a softening of the vortex lines with decreasing temperature. Our simple phenomenological model provides a qualitative explanation of the effect of disorder on a moving vortex structure.

Acknowledgements

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References

[1] For a review see D.J. Bishop, P.L. Gammel, D.A. Huse and C.A. Murray, Science 255 (1992) 165;
D.H. Huse, M.P.A. Fisher and D.S. Fisher, Nature (London) 358 (1992) 553.

[2] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin and V.M. Vinokur, Rev. Mod. Phys. 66 (1994) 1125;
M.V. Feigel'man, V.B. Geshkenbein, L.B. Ioffe and A.I. Larkin, Phys. Rev. B 48 (1993) 16641.

[3] H. Pastoriza, M.F. Goffman, A. Arribére and F. de la Cruz, Phys. Rev. Lett. 72 (1994) 2951;
E. Zeldov, D. Majer, M. Konczykowski, V.B. Geshkenbeiu, V.M. Vinokur and H. Shtrikman, Nature (London) 375 (1995) 373.

[4] H. Safar, P. Gammel, D.A. Huse, D.J. Bishop, W.C. Lee, J. Giapintzakis and D.M. Ginsberg, Phys. Rev. Lett. 70 (1993) 3800;
K.W. Kwok, S. Fleshler, U. Welp, V.M. Vinokur, J. Downey, G. Crabtree and M.M. Miller, Phys. Rev. Lett. 69 (1992) 3370.

[5] D.S. Fisher, M.P.A. Fisher and D.A. Huse, Phys. Rev. B 43 (1991) 130;
R.H. Koch, V. Foglietti, W.J. Gallagher, G. Koren, A. Gupta and M.P.A. Fisher, Phys. Rev. Lett. 63 (1989) 1511.

[6] L.L. Daemen, L.N. Bulaevskii, M.P. Maley and J.Y. Coulter, Phys. Rev. Lett. 70 (1993) 1167;
idem, Phys. Rev. B 47 (1993) 11292;
A.E. Koshelev, L.I. Glazman and A.I. Larkin unpublished.

[7] E.E. Rodriguez, M.F. Goffman, A. Arribére, F. de la Cruz and L.F. Schneemeyer, Phys. Rev. Lett. 71 (1993) 3175;
J.H. Cho, M.P. Maley, S. Fleshler, A. Lacerda and L.N. Bulaevskii, Phys. Rev. B 50 (1994) 6493.

[8] D. López, E. Rodriguez, G. Nieva, F. de la Cruz and S.W. Cheong, Physica B 194–196 (1994) 1977;
H. Safar, P.L. Gammel, D.A. Huse, S.N. Majumdar, L.F. Schneemeyer, D.J. Bishop, D. López, G. Nieva and F. de la Cruz, Phys. Rev. Lett. 72 (1994) 1272;
F. de la Cruz, D. López and G. Nieva, Philos. Mag. B 70 (1994) 773;

D. López, G. Nieva and F. de la Cruz, Phys. Rev. B 50 (1994) 7219.
[9] B. Janossy, D. Prost, S. Pekker and L. Fruchter, Physica C 181 (1991) 51;
K.E. Gray, D.H. Kim, B.W. Veal, G.T. Seidler, T.F. Rosenbaum and D.E. Farrell, Phys. Rev. B 45 (1992) 10071.
[10] D. López, G. Nieva, F. de la Cruz, H.J. Jensen and D. O'Kane, Phys. Rev. B 50 (1994) 9684.
[11] J.W. Ekin, B. Serin and J.R. Clem, Phys. Rev. B 9 (1974) 912;
K.K. Uprety and D. Domínguez, Phys. Rev. B 51 (1995) 5955;
E.A. Jagla and C.A. Balseiro, Phys. Rev. B, to be published.
[12] E. Osquiguil, M. Maenhoudt, B. Wuyts and Y. Bruynseraede, Appl. Phys., Lett. 60 (1992) 1627.
[13] M. Tetenbaum, L.A. Curtiss, B. Tani, B. Czech and M. Blander, Physica C 158 (1989) 371.
[14] Note that, as the anisotropy increases, a maximum in V_{bottom} gradually appears. Further investigation of this effect is in progress.
[15] J. Deak, L.F. Hou, P. Metcalf and M. McElfresh, Phys. Rev. B 51 (1995) 705.
[16] H. Safar, E. Rodriguez, F. de la Cruz, P.L. Gammel, L.F. Schneemeyer and D.J. Bishop, Phys. Rev. B 46 (1992) 14238;
R. Busch, G. Rics, H. Werthner, G. Kreiselmeyer and G. Saemann-Ischenko, Phys. Rev. Lett. 69 (1992) 522.
[17] V. Ambegaokar and B.I. Halperin, Phys. Rev. Lett. 22 (1969) 1364.