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Two different thermally activated flux-flow regimes in oxygen-deficient $YBa_2Cu_3O_{7-x}$ thin films

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We have measured the temperature dependence of the longitudinal resistivity of an oxygen-deficient $YBa_2Cu_3O_{6.45}$ thin film in perpendicular applied magnetic fields $B<12$ T. A crossover from a three-dimensional (3D) flux-line liquid to a quasi-2D liquid of vortices is identified which is characterized by a crossover line $B_{cr}=136.13*(1-T/T_c)/T$ ($T_c=30.35$ K, B_{cr} in T). In both 3D and 2D regimes, the dissipations are thermally activated. Above the crossover temperatures, the vortices are in a quasi-2D liquid state and the dissipation is dominated by the motion of edge dislocation pairs or vortex cutting and the activation energy is proportional to $(1-T/T_c)\ln B$. Below the crossover temperatures and above the irreversibility line, the vortices are in a 3D line liquid state, and the dissipation is governed by plastic deformation of the vortices through double kink nucleations in the vortices with activation energies $U_0 \propto (1-T/T_c)B^{-0.46}$.

Since the discovery of the high-temperature superconductors (HTSC's), tremendous efforts have been made to understand their magnetic phase diagram.[1] The H-T phase diagram is quite complicated due to the high superconducting transition temperatures T_c, short coherence lengths ξ, layered structures and large anisotropies γ. It is argued that the phase transition at the upper critical field H_{c2} is smeared out; instead a true phase transition appears at much lower temperatures which are commonly known as those corresponding to the "irreversibility line."[1] It is generally believed that the irreversibility line can be a vortex melting line or a vortex glass transition line, depending on the strength of the disorder in superconductors.[2] Below $H_{c2}(T)$ and above the irreversibility line, the vortices are in a liquid state which has a nonzero linear resistivity. Vortices in the liquid state can be pinned if the characteristic time of pinning τ_{pin} is smaller than the characteristic time of the thermal phononlike fluctuations τ_{ph}.[3] In a highly anisotropic superconductor, one vortex can essentially be viewed as a stack of quasi-two-dimensional (2D) "pancake vortices."[4] A crossover from three-dimensional (3D) to quasi-2D behavior of the vortices in a weakly Josephson-coupled superconducting system is anticipated at the crossover fields $B_{cr}(T)$.[5,6] Such dimensional crossover was found to exist for arbitrarily small interlayer coupling.[7,8] If $B_{cr}(T)$ lies above the irreversibility line, this crossover would correspond to a transition from a 3D liquid to a 2D liquid of vortices.

Using the analogy of a system of vortices at finite temperature with an interacting 2D Bose liquid at zero temperature, Nelson and Seung[9] proposed the possibility of the formation of an entangled vortex liquid phase. When the size of the sample is smaller than the characteristic entanglement length, a disentangled vortex liquid phase appears. Feigel'man[10] extended their arguments, taking into account the long-range interaction nature of the vortex system. Using the Lindemann criterion to determine the melting transition, he found that a direct transition from a vortex lattice (VL) to an entangled vortex liquid was rather improbable. An intermediate disentangled liquid phase should exist between the VL and an entangled vortex liquid. A similar conclusion was obtained by Li and Teitel from the results of numerical simulations.[11]

A thermally activated flux-flow (TAFF) behavior is commonly observed just above the irreversibility line in disordered superconductors. The activation energies extracted from the Arrhenius plot of $\ln\rho$ vs $1/T$ normally show a power-law or logarithmic dependence on the fields.[12,13] Different mechanisms have been proposed to explain such kinds of dependences. Using a multiterminal technique and a flux transformer configuration, Eltsev, Holm, and Rapp[14] and Safar *et al.*[15] observed a transition of the vortices from a 3D line liquid to a 2D liquid in $YBa_2Cu_3O_7$ (YBCO) crystals, while Busch *et al.*[16] found that in $Bi_2Sr_2CaCu_3O_8$ the vortices above the irreversibility line were basically in a 2D liquid state. In the meantime, Eltsev, Holm, and Rapp[14] also observed a crossover in the magnetic field dependence of the activation energies from a $1/B$ behavior at high fields to $-\ln B$ at low fields which was a result of the change of the dimensionality of the vortices.

Previous measurements on oxygen-deficient YBCO have been mainly concentrated on the effects of carrier densities on the normal-state properties. However, interest also lies in the mixed state of this kind of sample. It is found that with the decrease of the oxygen stoichiometry, the chains in oxygen-deficient $RBa_2Cu_3O_{7-x}$ ($R=$Y, Gd,. . .) become less effective in coupling the neighboring Cu-O bilayers, and thus the anisotropy increases.[17–21] When x was large enough, a crossover from 3D to 2D behavior of the vortices was observed.

In this paper, we report measurements of the temperature dependence of resistivity in an oxygen-deficient $YBa_2Cu_3O_{6.45}$ ($x=0.55$) thin film under different applied magnetic fields $B<12$ T. We observed two distinctly different TAFF regimes with the activation energies proportional to $(1-T/T_c)B^{-0.46}$ and $(1-T/T_c)\ln B$, respectively. We attribute these regimes to a transition of the vortices from a 3D line liquid to a quasi-2D liquid.

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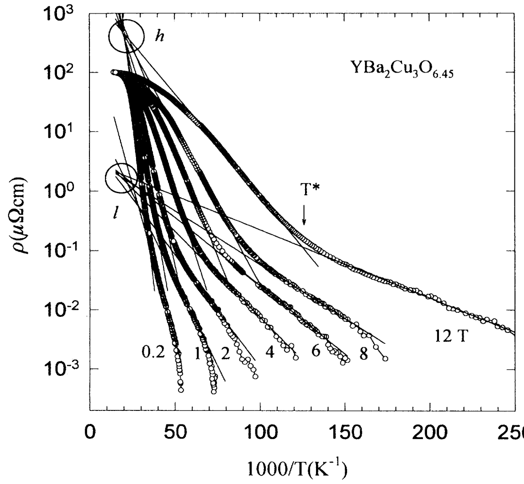

FIG. 1. Arrhenius plot of longitudinal resistivity $\rho(T,H)$ vs $1000/T$ at different perpendicular applied magnetic fields. The solid lines are the fits with TAFF theory. An example of the procedure which is used to determine $T^*(B_{cr})$ is shown in the plot for $H=12$ T.

The crossover line has been found to be consistent with the decoupling line of a Josephson-coupled superconducting system with moderate anisotropy.

The c-axis-oriented oxygen-deficient YBCO thin films were prepared using a simple procedure reported elsewhere.[22] The necessary oxygen concentrations were obtained by a controlled heat treatment of the film following a constant oxygen content line in the oxygen pressure-temperature (P_{O_2}-T) phase diagram of $YBa_2Cu_3O_{7-x}$. In this work, we used a $YBa_2Cu_3O_{7-x}$ thin film with a nominal oxygen concentration with $x=0.55$ as determined from the P_{O_2}-T phase line. The thickness of the sample was 3000 Å.

The film was photolithographically patterned for four-terminal measurements. A standard low-frequency ac lock-in technique was used to measure the longitudinal resistivity (ρ_{xx}). A probe current of 10 μA was applied during the measurements, corresponding to a current density of 1.5 A/cm^2. The magnetic fields were generated by a 15 T Oxford superconducting magnet. In all the measurements, the magnetic fields were applied perpendicular to the ac current and the film plane.

Figure 1 shows the Arrhenius plot of the temperature dependence of ρ_{xx} for this film under different perpendicular fields. It clearly reveals that in each field corresponding to resistivities below $0.1\rho_n$ (ρ_n being the normal-state resistivity), there are two distinct parts where $\ln\rho$ shows linear dependences upon $1/T$ with different slopes. These results are independent of the probe currents as confirmed by our measurements with an ac current of 1 μA at several fields. This behavior is typical for dissipations induced by TAFF. We notice that very similar $\ln\rho$ vs $1/T$ behavior was observed by White, Kapitulnik, and Beasley[23] on MoGe thin films and MoGe/Ge multilayers and by Koorevaar[24] on NbGe/Ge multilayers. As discussed in Ref. 25, a linear slope in the Arrhenius plot indicates the validity of a $U=U_0(1-T/T_c)$ dependence of the activation energy and therefore from the slopes we can obtain the U_0 values. From these two linear parts in each field, we extract the activation energies for different temperature regimes. The activation energies for these two temperature regimes as a function of B are shown in Fig. 2. From a best fit (see solid lines in Fig. 2) we find that the activation energies U_0^h from the higher temperature parts are $U_0^h(B)=381.8-122.9*\ln B$ [Fig. 2(b)], while those U_0^l from the lower temperature parts follow a power-law behavior with the exponent $n=-0.46$, i.e., $U_0^l(B)=119.2/B^{0.46}$ [Fig. 2(a)]. In these expressions for U_0^h and U_0^l B should be taken in T.

Extrapolating the fits to higher temperatures, we find that the fits for both the higher and lower temperatures (we define them as regime h and regime l from now on) cross at nearly the same temperature T_c (see the crossing points encircled by solid lines in Fig. 1). We see that

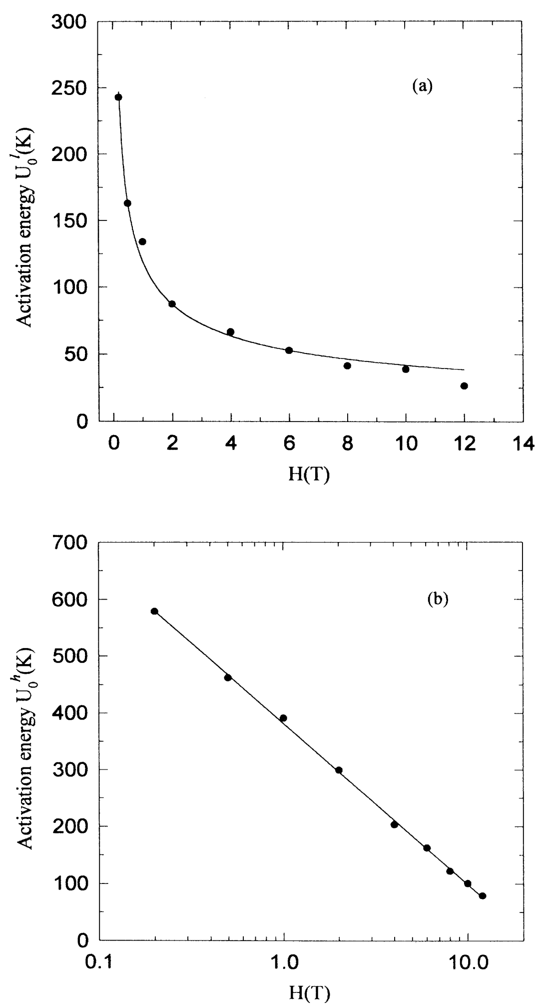

FIG. 2. Activation energies obtained from the slopes of Fig. 1 in (a) the low-temperature parts and (b) high-temperature parts. The solid lines show the best fits.

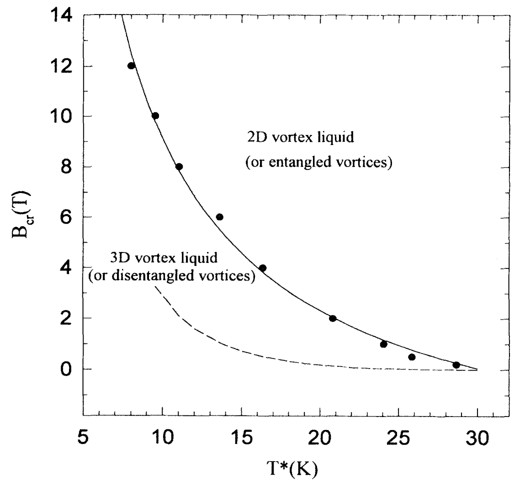

FIG. 3. Decoupling temperatures T^* as a function of applied magnetic fields. The solid line is a fit by Eq. (1) in the text with $\gamma=26$. The dashed line is the 3D melting line calculated by Eq. (2) with the Lindemann number $c_L=0.1$.

while the prefactor for the resistivity in regime h is nearly one order of magnitude higher than the normal-state resistivity at T_c, as often observed in previous experiments,[12] the prefactor for regime l is nearly two orders lower than the normal-state resistivity. Moreover, from the shift of characteristic temperature T^* separating regime h and regime l, we obtain the crossover line $T^*(B_{cr})$. In Fig. 3 we present the obtained B_{cr}-T^* diagram.

It is well known that, above the irreversibility line, the vortices are melted and they are in liquid state. In a disordered superconductor the dissipation in the liquid state is governed by TAFF.[3] The different field dependences of the activation energies suggest different dissipation mechanisms in these two temperature regimes. Glazman and Koshelev have studied the effects of thermal fluctuations on the superconducting properties in a layered superconductor.[5] They found that the vortex system undergoes two distinct transitions. Upon heating from the VL state, first there is a transition characterized by the loss of phase coherence in planes perpendicular to the applied magnetic fields, while phase coherence is retained parallel to the field. Then at a higher temperature, phase coherence is lost in the direction parallel to the field as well. A similar conclusion was reached by Daemen *et al.*[6] and by Hellerqvist *et al.*[26] later on. Thus in a Josephson-coupled superconducting system, a crossover from a 3D liquid to a decoupled quasi-2D liquid of vortices is possible under some circumstances.

Since a $(1-T/T_c)\ln B$ dependence of the activation energy is often observed in superconductors where the vortices are in the 2D regime,[13,25,27] this simple fact suggests that in our sample in the temperature regime h the vortices are in a quasi-2D state. The crucial question is, however, does the obtained $B_{cr}(T^*)$ line correspond to a 3D liquid or to 2D liquid transition? Daeman *et al.*[6] have calculated the decoupling line in a Josephson-coupled layered superconducting system in a self-consistent manner. They took into account the renormalization of the Josephson coupling by thermal fluctuations and static disorder, and they obtained the decoupling fields as

$$B_{cr}(T)=\frac{\Phi_0^3}{16\pi^3 k_B T s e \lambda_{ab}^2(T)\gamma^2} \tag{1}$$

for moderate anisotropy when $\xi_{ab}(0)/s \ll \gamma \ll \lambda_{ab}(0)$. Here $\Phi_0=2.07\times10^{-7}$ G cm^2 is the flux quantum, $e=2.718\ldots$, $\gamma=\lambda_c/\lambda_{ab}$ is the anisotropy parameter at $B=0$, λ_{ab} and λ_c are the penetration depths in the plane and along the c axis, respectively, and s is the distance between the superconducting Cu-O planes. Since $\lambda_{ab}^2(T)\propto(1-T/T_c)$, therefore $B_{cr}(T)\propto(1-T/T_c)/T$.

We find that the B_{cr}-T^* line we obtained above can be nicely fitted by Eq. (1) with reasonable parameters. The fitted result is $B_{cr}=136.13^*(1-T/T_c)/T$ as shown in Fig. 3 by the solid line. The fitted value of T_c is 30.35 K which is nearly the same as the zero resistivity onset temperature in our sample. Using the value of $\lambda_{ab}(0)\approx2240$ Å obtained by Gray *et al.*[18] on $YBa_2Cu_3O_{6.45}$ single crystals from magnetic susceptibility measurements and $s\approx11.6$ Å, we obtain $\gamma\approx26$ from this fitting result. The fitted γ value is quite large compared with those for fully oxidized YBCO thin films. It is in reasonable agreement with those values of similar samples obtained from equilibrium torque magnetometry measurements.[17]

We can also make an estimation of the 3D melting fields using the Lindemann criterion. For 3D vortex fluctuations, when $B\ll B_{c2}$, the melting temperatures are given by[28]

$$B_m^{3D}(T)=\frac{c_L^4\Phi_0^5}{16\pi^4\gamma^2\lambda_{ab}^4(T)(k_B T)^2}, \tag{2}$$

where $c_L\approx0.1-0.2$ is the Lindemann number. With $\gamma=26$, $\lambda_{ab}(0)=2240$ Å, and $c_L=0.1$, we find that the melting line lies well below the decoupling line as shown in Fig. 3 by the dashed line. Therefore, in the temperature regime l, the vortices are in a 3D line liquid state.

As discussed by Geshkenbein *et al.*[29] and by Vinokur *et al.*,[3] the dissipation in a line liquid can be developed via the plastic deformation of the vortices. The corresponding activation energy is associated with the energy required to create a double kink in the vortex which is the free energy of two vortex segments along the ab plane with the length of $a_0\approx(\Phi_0/B)^{1/2}$, the average distance between the vortices. Using anisotropic Ginzburg-Landau theory, the barrier for this plastic movement can be estimated to be

$$U_{pl}=2E_v a_0\approx\frac{\Phi_0^2}{8\pi^2\tilde{\lambda}^2(T)}\left[\frac{\Phi_0}{B}\right]^{1/2}, \tag{3}$$

where E_v is the vortex energy per unit length along the ab planes and $\tilde{\lambda}^2=\lambda_{ab}\lambda_c$. Therefore the activation energy $U_0=U_{pl}\propto(1-t)/\sqrt{B}$ is predicted which is in good agreement with our observations. To make an order of magnitude estimate for the magnitude of U_{pl}, we use the above-mentioned values for γ and λ_{ab}. This gives us

$U_0 \approx 4000$ K at 1 T, which is more than one order higher than the activation energy we obtained. Due to the uncertainty of the values we used above, it is difficult to get a quantitative fit. For example, if we use those values obtained by Chien *et al.*[30] with $\gamma \approx 100$ and $\lambda \approx 5000$ Å, we have $U_0(1\ \mathrm{T}) \approx 70$ K, which is slightly lower than U_0^l at 1 T. Nevertheless, the double kink mechanism gives us at least a qualitative explanation.

As the temperature increases above the decouple line, in the temperature regime h, the vortices lose their coherence along the field direction and they are in a quasi-2D liquid state. There are a lot of reports on the measurements of the activation energies for 2D vortex system. Most of the time a $(1-T/T_c)\ln B$ dependence of the activation energies was found as in our case. There are several mechanisms which can be responsible for these particular temperature and field dependences.

The first is the generation of edge dislocation pairs in the vortices with a short translational correlation length R_c.[31,32] The activation energy is associated with the energy required to nucleate an edge dislocation pair in the vortices. The typical energy for a small pair, which corresponds to a vortex interstitial or a vacancy, is

$$U_e = \frac{\Phi_0^2 s}{16\pi^3 \lambda_{ab}^2(T)} \ln(B_0/B) , \tag{4}$$

where $B_0 \approx \Phi_0/\xi^2(T)$. We note that Eq. (4) gives a $(1-T/T_c)\ln B$ dependence of U_e as we observed. Inserting the values for $s \approx 11.6$ Å and $\lambda_{ab} \approx 2240$ Å, we have $U_e = 104^*(\ln B_0 - \ln B)$, which is in quantitative accordance with our results in the temperature regime h.

The second is the motion of thermally activated vortex-antivortex pairs which was recently proposed by Jensen *et al.*[33] where the activation energy was found to be $E_{V-\bar{V}} = (\Phi_0^2 s/4\pi\lambda_{ab}^2(T))\ln(B_0/B)$. Therefore, a $(1-T/T_c)\ln B$ dependence of the activation energy is also predicted. We notice that $E_{V-\bar{V}}$ is more than one order of magnitude higher than U_e. Given the high applied fields and relatively low temperatures we worked with, we think that the realization of the mechanism is less probable than that of the edge dislocation pairs considered in Ref. 31.

It should be noticed that White, Kapitulnik, and Beasley[27] also observed a kink in the R-T curves on Nb/Ge multilayers and they attributed that kink to an interlayer decoupling transition. However, they found a downward kink instead of an upward kink as found by us. This should be related to the strength of disorders, the anisotropy of the materials, and the dissipation processes. As is well known, the basic unit in a flux creep event is one flux bundle, which can be made of one or many vortices. The more vortices one flux bundle includes, the fewer the number of the flux bundles. If we apply a parallel resistor model, and we treat the resistivity as that arising from the summation of all the contributions from the flux bundles, then the prefactor will be inversely proportional to the total number of flux bundles. Since the sample we used here was an oxygen-deficient sample, it is well known that when the oxygen is removed from a fully oxydized YBCO, the Cu-O chains are depopulated, resulting in oxygen vacancies in the chains. Therefore, the dominant pinning centers in this sample should be point defects which are uniformly distributed in the sample. In such a situation, it is quite possible that vortices are in the armophous state,[34] i.e., the Larkin length $L_p \approx a_0$, so one flux bundle is made up of one vortex. That is why the prefactor in the regime l is so small. On the other hand, in the temperature regime h, as mentioned above, the dissipations may be dominated by the edge dislocation pairs which can be roughly viewed as large vortex bundles, and thus a large prefactor appears.

Up to now, we have explained all the essential features we observed in our experiments within the picture of a dimensional crossover from a 3D line liquid to a quasi-2D liquid of vortices due to the Josephson decoupling. However, there is another possibility. As we mentioned in the introductory part, in the vortex liquid state, a crossover from a disentangled vortex liquid to an entangled one is possible. Is it possible then that our observed B_{cr}-T^* line is an entanglement-disentanglement crossover line? As suggested by Nelson,[35] an important characteristic of an entangled phase is the "entanglement length" l_z, i.e., the spacing along the field direction between collisions or close encounters between vortices. When $l_z = L$, the sample thickness, a disentanglement occurs and the vortices will be in a 3D liquid state if the temperature is lower than the decoupling temperature. The calculations by Nelson in a continuum model show that the crossover from an entangled phase to a disentangled phase occurs at

$$B_{\mathrm{cr}}(T) = \frac{\Phi_0 \varepsilon_0}{\gamma^2 L k_B T} , \tag{5}$$

where $\varepsilon_0 = \Phi_0^2 \ln\kappa / 16\pi^2\lambda_{ab}^2(T)$ is the line tension for a vortex. A fit to Fig. 3 gives us $\gamma = 8.6$, which is smaller than the reported values.[17] In our determination of the crossover line, we have used the result by Nelson that this crossover happens when $l_z = L$. The numerical simulation suggest that $l_z = L$ may not be the unique criterion to determine the entanglement-disentanglement crossover. The actual length can be much smaller than the sample thickness. If this is true, then a fit to our data will give us a much larger value of γ.

As discussed by Nelson[9] and by Obukhov and Rubinstein,[36] in an entangled vortex phase, the favorable dissipation process could be vortex cutting and reconnection. The activation energy for TAFF is the energy required for the vortex cutting which has been calculated by Obukhov and Rubinstein. Following the suggestion of Obukhov and Rubinsten,[36] we can estimate the energy required for vortex cutting in the following way. Two nearly parallel vortices can cut each other, if the distance between these two vortices has been decreased from the mean vortex spacing a_0, to the dimension of the core, ξ_{ab}. Neglecting the energy due to the elongation of the vortices for vortex cutting, the energy required for such a process is

$$U_{\mathrm{cut}} = \frac{\Phi_0^2 s}{32\pi^2 \lambda_{ab}^2(T)} \ln(B_0/B) . \tag{6}$$

Thus a $(1-T/T_c)\ln B$ dependence is obtained. An order of magnitude estimate based on Eq. (6) gives us $U_{\rm cut} \approx 3600{*}\ln(B_0/B)$ K which is considerably higher than U_0^h. However, as pointed out by Brandt and Sudbø,[37] the energy for vortex cutting can be much lower if the vortices are cut by tilting with respect to each other. Therefore, Eq. (6) can only give us a qualitative explanation.

Thus, at the present stage, we cannot exclude the possibility that our obtained $B_{\rm cr}$-T^* line could also represent an entanglement-disentanglment crossover (Fig. 3). Further experiments on single crystals using the flux transformer geometry could possibly give us an answer.

In summary, we observed two distinct TAFF regimes in the vortex liquid state with the activation energies characterized by $(1-T/T_c)\ln B$ (high-temperature regime, h) and $(1-T/T_c)B^{-0.46}$ (lower temperature regime, l), respectively. In the temperature regime l the vortices are in a 3D line liquid state and the dissipation is governed by the plastic deformation of the vortices through the nucleation of double kinks. While in the temperature regime h, the vortices are in a quasi-2D liquid state; the main dissipation process is the nucleation of dislocation pairs or simulations cutting of vortices.

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