Transition from Activated to Diffusive Behavior in the Vortex-Liquid State in $YBa_2Cu_3O_7$

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In the vortex-liquid state in $YBa_2Cu_3O_7$, there exist two distinct dissipative states separated by a field H_k. Below H_k, the resistivity is strongly field activated, with a prefactor that is anomalously enhanced over the normal-state resistivity ρ_N by ~ 12 orders of magnitude. At H_k, the prefactor collapses to a temperature-independent value equal to ρ_N, and the vortex motion becomes diffusive. The existence of the H_k boundary is also reflected in the anomalous behavior of the Hall resistivity.

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The nature of vortex motion and dissipation in the oxide superconductors is a subject of strong current interest.[1-9] For a range of fields and temperatures, the resistivity shows strongly activated behavior, with a temperature-dependent activation energy $U(T)$.[1] The existence of different phases of the flux lattice was initially suggested by mechanical-oscillator experiments.[2] These studies have been interpreted in terms of a vortex-glass phase or an entangled phase.[3,4] Recently, Koch *et al.*[5] and Gammel, Schneemeyer, and Bishop[6] have reported evidence, from current-voltage (I-V) studies on $YBa_2Cu_3O_7$, for a vortex solid-to-liquid transition at a "melting field" H_g. Worthington, Holtzberg, and Feild[7] (WHF) have further proposed a phase boundary line that occurs at the higher field H_k. Although the regime between H_g and H_k has been discussed in terms of a "pinned" liquid,[8] much remains obscure. In $YBa_2Cu_3O_7$, the situation is confused by the lack of an accurate description of the field dependence of the resistivity. Previous studies[1,7,9,10] have been, by and large, measurements of ρ_{xx} versus temperature in a *constant* field. Such results are difficult to analyze because of the strong temperature dependence of the activation energy near T_c, as noted by Palstra *et al.*[10] Conflicting conjectures on the field dependence exist in the literature.

We report here detailed measurements of ρ_{xx} and the Hall resistivity ρ_{xy} in three (microtwinned) single crystals of $YBa_2Cu_3O_7$ in intense fields. All measurements are performed in the "liquid" state above H_g, where previous studies show that the I-V curves are Ohmic.[5,6] We find strong evidence that the field H_k separates two distinct vortex phases in the liquid state. Previously, WHF[7] identified H_k by a shoulder in the curve of ρ_{xx} versus temperature (T) in fixed field. Although a transition was proposed[7] to occur at H_k, no supporting evidence was presented. We find that the dissipative mechanisms are, in fact, *qualitatively* different in the two phases. As the field is varied, the dissipation abruptly changes from strong activation to diffusive behavior when H_k is exceeded.

Contacts to the crystals with low resistances (<0.1 Ω) were formed by evaporating silver contact pads, and then annealing at 500 °C for 2 h. The magnetic field, parallel to **c**, is slowly swept from +15 to −15 T while the temperature is regulated to a stability of ±30 mK. In Fig. 1, we display the field dependence of the Hall resistivity ρ_{xy} (upper panel) in sample 1. As reported previously,[11] the Hall resistivity shows a striking negative minimum in weak fields. In high fields, however, it approaches a linear dependence on field, with a slope slightly larger than that of 93 K (dashed line). The resistivity (lower panel) displays a deceptively smooth increase with field. Close examination of the curves shows a break in slope of the field H_k (indicated by the arrows). A more revealing way to view the data is to plot $\log\rho_{xx}$ against $1/H$ (Fig. 2). In the high-field limit (upper panel) $\log\rho_{xx}$ is now observed to vary linearly with $1/H$ (dotted lines). In the opposite limit of weak fields (lower panel), $\log\rho_{xx}$ also varies linearly with $1/H$, but with a slope that is an order of magnitude larger. Evi-

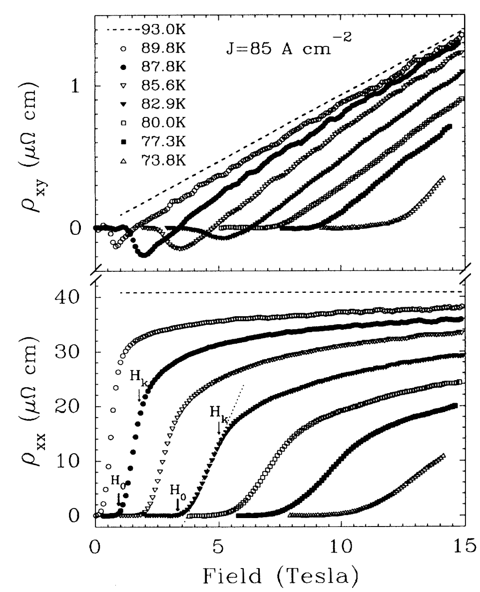

FIG. 1. Upper panel: Field dependence of the Hall resistivity (**J**⊥**c**, **H**∥**c**) at various temperatures (sample 1). The resistivity ρ_{xx}, measured simultaneously, is displayed in the lower panel. At the field H_k (where the curve breaks from the dotted line), a transition to diffusive motion occurs. H_0 is the field at which ρ_{xx} exceeds $0.01\rho_N$.

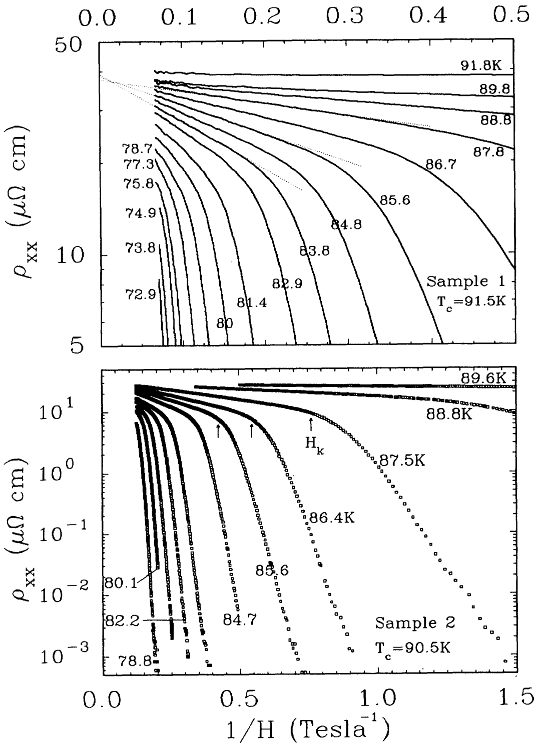

FIG. 2. Upper panel: Plot of $\log\rho_{xx}$ against $1/H$, amplifying the regime above H_k in sample 1 ($J \sim 3$ A/cm^2). The dotted lines indicate the convergence of $\log\rho_{xx}$ to a common point. Lower panel: Plot of $\log\rho_{xx}$ vs $1/H$, emphasizing the region below H_k in sample 2. $\text{Log}\rho_{xx}$ is linear in $1/H$ over 3 to 4 decades in ρ_{xx}. The intercept $\log\rho_0$ at $H^{-1}=0$ is strongly temperature dependent. (Arrows indicate H_k.)

dently, an abrupt change in slope occurs at the crossover field H_k (arrows).

We first discuss the high-field regime. Because $\log\rho_{xx}$ is linear in $1/H$, we may write

$$\rho_{xx}(T,H) = \rho_0' \exp\{-a'(1-t)^{q'}/H\} \quad (H > H_k), \tag{1}$$

where $t = T/T_c$. From the data, a' and q' have the values 146 T and 1.50, respectively. [Near H_k, Eq. (1) becomes invalid because of the rapid change in slope.] An interesting feature in Fig. 2 (upper panel) is the convergence of the high-field curves to a common value very close to ρ_N, in the limit $1/H \to 0$ (see dotted lines). Thus, the prefactor ρ_0' in Eq. (1) is temperature independent and $\approx \rho_N$. Identifying the expression within curly brackets in Eq. (1) as the activation energy U' divided by $k_B T$, we find that $U' < k_B T$, so that vortex motion is *diffusive* in the high-field regime. [At H_k, the ratio ρ_{xx}/ρ_N varies from ~ 0.3 at 74 K to ~ 0.8 at 89 K. Contrary to WHF,[7] flux flow, of the Bardeen-Stephen (BS) form $\rho_N H/H_{c2}$, is not observed at any field or temperature in this regime (H_{c2} is the upper critical field).]

In contrast, the vortex motion below H_k is strongly activated in both field and temperature. As shown in the lower panel of Fig. 2, $\log\rho_{xx}$ is linear in $1/H$ over a large range in ρ_{xx} (3–4 decades). As mentioned above, the sharp change in slope signals a qualitative change in the dissipative process. A more striking difference between the two field regimes is seen in the prefactor of ρ_{xx}. Instead of the temperature-independent value obtained above H_k, the prefactor $\rho_0(T)$ below H_k increases exponentially with reduced temperature. In this regime, we write the full expression for the resistivity as

$$\rho_{xx}(T,H) = \rho_{0c} e^{g(t)} \exp\{-a(1-t)^q/TH\} \tag{2}$$
$$(H_g < H < H_k),$$

where $a = 5.55 \times 10^5$ TK, $q = 1.70$, and $\rho_{0c} \approx \rho_N$. The prefactor $\rho_0(T) = \rho_{0c} e^{g(t)}$ increases rapidly with $1-t$, attaining values that are 13 orders of magnitude larger than ρ_N. [Figure 3 (upper panel) shows how $g(T)$ varies with T.] This giant enhancement provides, arguably, the strongest evidence to date that vortex motion in this regime is incompatible with models invoking thermal activation of single vortices, all of which predict a prefactor either equal to ρ_N or $\rho_N H/H_{c2}$ (Ref. 12). The observed activation energy $U(T,H) = a(1-t)^q/H$ is very large.

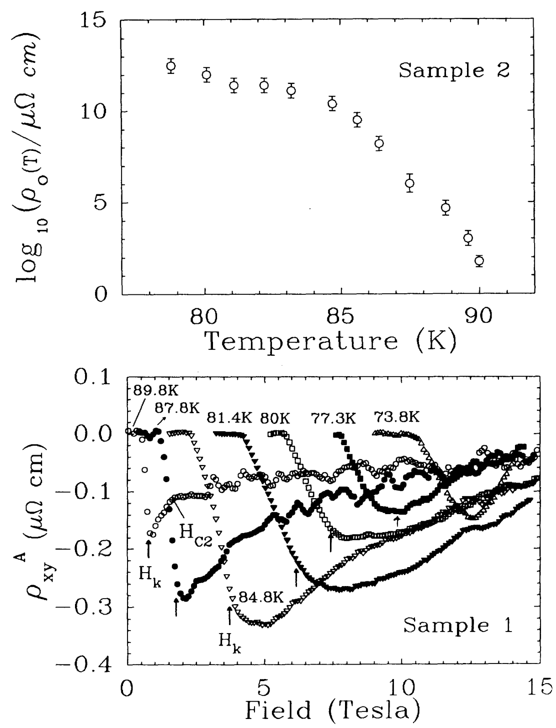

FIG. 3. Upper panel: Temperature dependence of the prefactor $\rho_0(T)$ in sample 2 obtained by extrapolating the straight lines in Fig. 2, lower panel, to $H^{-1}=0$. Below 85 K, $\rho_0(T)$ is enhanced over the value of ρ_N by 11 to 13 orders of magnitude. Lower panel: Field dependence of the anomalous part of the Hall resistivity ρ_{xy}^A at various temperatures (sample 1). Arrows indicate H_k determined from Fig. 2.

[It is instructive to compare U with the condensation energy in the region surrounding a single vortex disk, $U_{\text{disk}} \approx 2.34\times10^5(1-t)^{3/2}/B$ K.[13]] U is a factor 1 to 3 larger than U_{disk}. The surprisingly large energy scale ($\sim$20 eV) set by U_{disk} implies that thermal activation of single vortices would lead to an essentially unobservable ρ_{xx} ($\sim10^{-14}$ $\mu\Omega$ cm), if the prefactor were $\approx\rho_N$ (see also Ref. 10). Our analysis shows that the small exponential is, in fact, compensated by a very large prefactor, so that the observed ρ_{xx} falls in the range of $10^{-2}\rho_N$. The large prefactor suggests activated vortex motion that is correlated over very large volumes. This favors models invoking line entanglement or glassy behavior, over single-vortex activation models. When the field H_k is exceeded, *the prefactor collapses over several orders of magnitude to the value* ρ_N. This remarkable contraction, together with the sharp change in activation energy, signals a transition between different vortex states at H_k.

A second interesting feature in Fig. 2 is the linear variation of $\log\rho_{xx}$ vs $1/H$ over 3 to 4 decades in ρ_{xx} when H is below H_k. As noted by Palstra *et al.*,[10] there is no evidence for a "threshold" field for the onset of dissipation, apart from the melting field H_g, which lies below our range of measurements. (For later discussion, however, we find it convenient to define the onset field H_0 as where $\rho_{xx}=0.01\rho_N$. Although not an intrinsic quantity, H_0 is often treated as the closest analog of the "depinning" field H_p, which *has* an intrinsic meaning in low-T_c superconductors.)

We discuss the Hall effect next. In type-II superconductors, a Hall signal arises because the vortex-line velocity makes a small angle θ_H with the Lorentz-force direction $\mathbf{J}\times\mathbf{H}$ ($\mathbf{J}$ is the current density). In conventional superconductors (e.g., $2H$-$NbSe_2$),[14] both ρ_{xx} and ρ_{xy} increase *linearly* with the reduced field (H-H_p) when the depinning field H_p is exceeded. The Hall resistivity and Hall angle are well described by

$$\rho_{xy}=\beta\rho_N(H-H_p)/H_{c2},\quad \tan\theta_H=\beta\,, \tag{3}$$

where the parameter β is independent of field, but varies linearly with the reduced temperature $(1-t)$. Its magnitude in $2H$-$NbSe_2$ (Ref. 14) is in good agreement with the Nozières-Vinen[15] (NV) value $\beta_{\text{NV}}=eH_{c2}\tau/m$. ($\tau$ and m are the electron relaxation time and effective mass in the vortex core.)

Although our results for ρ_{xx} in $YBa_2Cu_3O_7$ are incompatible with the conventional BS form ($\rho_N H/H_{c2}$) at all fields, the Hall resistivity appears to approach the behavior in Eq. (3) in intense fields (Fig. 1, upper panel). Since the observed electric fields are additive in the mixed state, it is convenient to separate the observed ρ_{xy} into the "conventional" part [Eq. (3)], and an anomalous part ρ_{xy}^A, viz., $\rho_{xy}=\rho_{xy}^0+\rho_{xy}^A$. To determine ρ_{xy}^0, we draw a straight line through H_0 at each temperature, with slope proportional to $1/T$ (reflecting the temperature dependence of ρ_{xy} in the normal state). Subtracting this component from the total ρ_{xy}, we obtain ρ_{xy}^A, which is displayed in Fig. 3 (lower panel).

Both the initial linear variation and the sharp minimum noted for ρ_{xy} are more prominently observed in ρ_{xy}^A, particularly near T_c. Moreover, the anomalous contribution is seen to extend down to 74 K (which is not as apparent in Fig. 1).[16] Inserting the values of H_k deduced from ρ_{xx} (arrows), we find that H_k occurs near the minimum in ρ_{xy}^A. In low fields, ρ_{xy}^A is observed to increase very rapidly, starting near H_0. Although ρ_{xy}^A appears to be roughly linear in the reduced field $(H-H_0)$, it actually increases *exponentially* with field in close similarity with ρ_{xx} [Eq. (2)]. The position of H_k actually indicates where ρ_{xy}^A first deviates significantly from the exponential increase. In the diffusive regime above H_k, ρ_{xy}^A decays gradually to zero (i.e., ρ_{xy} approaches the conventional NV behavior). Thus, the unusual Hall behavior is intimately associated with crossing the phase boundary at H_k.

To relate our results to previous work, we refer to the vortex phase diagram of $YBa_2Cu_3O_7$ in Fig. 4. Data for H_k determined from ρ_{xy} and from ρ_{xx} (at two different

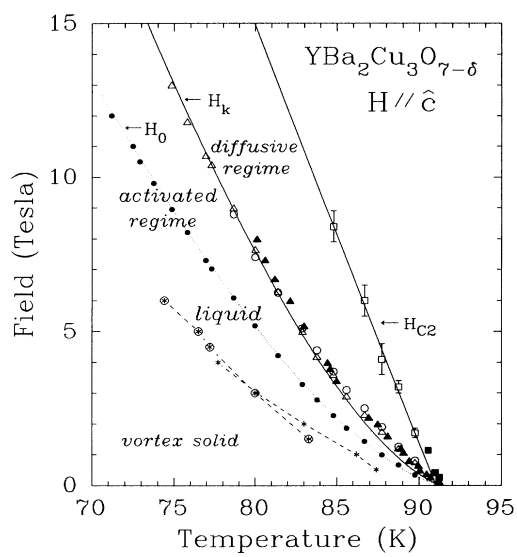

FIG. 4. Phase diagram of the vortex system in $YBa_2Cu_3O_7$. The solid line, $H_k=170.5(1-t)^{3/2}$ T, is a fit to the data for H_k. The open triangles (open circles) are H_k determined from the crossover field in ρ_{xx} (minimum of ρ_{xy}^A) taken with $J=85$ A/cm^2. The solid triangles are determined from the kink in the ρ_{xx} data observed with low J (3 A/cm^2). The "onset" field H_0 (not intrinsic) is indicated by the small solid circles and fitted by $H_0=115.3(1-t)^{3/2}$ T (dotted line). The melting line H_g is located by data from Koch *et al.* (Ref. 5) (asterisks) and Gammel, Schneemeyer, and Bishop (Ref. 6) (asterisks in circles). The H_{c2} line is identified by kinks in our data for ρ_{xx} (solid squares) and ρ_{xy}^A (open squares).

J's) are displayed. Also shown are the "solid-liquid" melting line $H_g(T)$ and the nonintrinsic line H_0. The "irreversibility" line determined from ac susceptibility measurements is frequency dependent. At high frequencies (40 MHz)[7,17] it approaches the position of the H_0 line, whereas at low frequencies (100 Hz)[18] it lies closer to H_g.

Our results suggest the following physical picture. As the field is increased from zero at fixed temperature, the vortex solid undergoes a melting transition at the field H_g, as previously proposed.[3,5,6] From our studies, the liquid state above H_g possesses a number of unusual transport properties. Between H_g and H_k, ρ_{xx} increases by 3 to 4 decades with field, as described by Eq. (2). In this state, the anomalously large prefactor (compensating the large activation energy) suggests vortex motion that is correlated over very long length scales, rather than thermal activation of individual vortices. The anomalous part of the Hall voltage is negative, and increases exponentially like the resistivity. Together, the giant prefactor and the anomalous Hall signal may provide a rather stringent test for the correct model. When H_k is exceeded, the correlated liquid state makes a transition to a second state in which vortex motion is diffusive. At present, the evidence is insufficient to distinguish a real phase transition occurring at H_k from a rapid change in the vortex dissipation mechanism. (The former would involve a diverging coherence length and an identifiable order parameter.) However, the observed collapse of the prefactor over 12 orders of magnitude and the abrupt change of the activation energy make the phase-transition case an attractive possibility. Above H_k, the vortex liquid loses all correlations responsible for activation of large coherent volumes. The small value of U' above H_k [U' is ~ 20 times smaller than U_{disk} (Ref. 13)] and the collapse of the prefactor to a constant close to ρ_N suggest the picture of weakly interacting vortices diffusing in a disordered potential with average barrier heights smaller than $k_B T$.

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[1]T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. Lett. **61**, 1662 (1988); T. T. M. Palstra *et al.*, Appl. Phys. Lett. **54**, 763 (1989).

[2]P. L. Gammel, L. F. Schneemeyer, J. V. Waszczak, and D. J. Bishop, Phys. Rev. Lett. **61**, 1666 (1988).

[3]M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989).

[4]D. R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988).

[5]R. H. Koch, V. Foglietti, W. J. Gallagher, G. Koren, A. Gupta, and M. P. A. Fisher, Phys. Rev. Lett. **63**, 1511 (1989).

[6]P. L. Gammel, L. F. Schneemeyer, and D. J. Bishop, Phys. Rev. Lett. **66**, 953 (1991).

[7]T. K. Worthington, F. H. Holtzberg, and C. A. Feild, Cryogenics **30**, 417 (1990).

[8]V. M. Vinokur, M. V. Feigel'man, V. B. Geshkenhein, and A. I. Larkin, Phys. Rev. Lett. **65**, 259 (1990).

[9]W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort, R. Hulscher, and J. Z. Liu, Phys. Rev. Lett. **64**, 966 (1990).

[10]T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. B **41**, 6621 (1990).

[11]M. Galffy and E. Zirngiebl, Solid State Commun. **68**, 929 (1988); Y. Iye, S. Nakamura, and T. Tamegai, Physica (Amsterdam) **159C**, 616 (1989).

[12]M. V. Feigel'man, V. B. Geshkenbein, and A. I. Larkin, Physica (Amsterdam) **167C**, 177 (1990); M. Inui, P. B. Littlewood, and S. N. Coppersmith, Phys. Rev. Lett. **63**, 2421 (1989).

[13]$U_{\text{disk}} \approx H_c^2 \phi \xi_c / 8\pi B$, where ϕ is the flux quantum and ξ_c the coherence length along **c**. From $\kappa = 500$, $H_{c2}(0) \approx 100$ T, $\xi_c \approx 2$ Å, we estimate $U_{\text{disk}} \approx 2.34\times 10^5 (1-t)^{3/2}/B$ K. Below H_k, $U \approx 2.4 U_{\text{disk}}$, but above H_k, $U' \approx 0.056 U_{\text{disk}}$.

[14]T. W. Jing and N. P. Ong, Phys. Rev. B **42**, 10781 (1990).

[15]P. Nozières and W. F. Vinen, Philos. Mag. **14**, 667 (1966).

[16]At temperatures below 80 K, the anomalous part ρ_{xy}^A is too small to drive the total ρ_{xy} negative. However, it distorts the observed ρ_{xy} near H_0, and gives the false impression that the Hall signal is "delayed" relative to the "onset" field H_0 of ρ_{xx} (see 77.3- and 80.0-K curves in Fig. 1).

[17]A. P. Malozemoff, T. K. Worthington, Y. Yeshurun, and F. Holtzberg, Phys. Rev. B **38**, 7203 (1988).

[18]J. van den Berg, C. J. van der Beek, P. H. Kes, J. A. Mydosh, A. A. Menovsky, and M. J. V. Menken, Physica (Amsterdam) **153-155C**, 1465 (1988).