Hall effect and flux dynamics in $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ multilayers in the mixed state

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We report on the temperature and magnetic-field dependence of both the longitudinal resistivity ρ_{xx} and Hall resistivity ρ_{xy} of a $[YBa_2Cu_3O_7(72\ \text{Å})/PrBa_2Cu_3O_7(12\ \text{Å})]_{25}$ multilayer in the mixed state. Near T_c, the Hall resistivity ρ_{xy} undergoes a sign reversal in the low-field region, while at the temperature where ρ_{xy} shows a minimum, the vortices have the highest mobility. An analysis of the Hall conductivity σ_{xy} reveals that σ_{xy} can be successfully described by the two terms which are related to the quasiparticle excitations and the motion of free vortices, respectively. The high-T_c multilayers also demonstrate the Hall sign reversal and scaling behavior $\rho_{xy} \propto \rho_{xx}^2$, previously reported for as-grown high-T_c compounds.

I. INTRODUCTION

The sign reversal of the Hall resistivity (ρ_{xy}) near the superconducting transition temperature T_c and the scaling behavior $\rho_{xy} \propto \rho_{xx}^2$ between ρ_{xy} and the longitudinal resistivity ρ_{xx} in high-T_c superconductors are still unsolved experimental facts.[1–11] Since the sign reversal is generally found in the flux-flow regime of both high-T_c and conventional superconductors, it is believed that the sign reversal is closely related to the flux dynamics in the mixed state, although a two-band model,[2] and a fluctuation model[3] have also been proposed.

To understand the origin of the sign reversal, it is suggested that an upstream of the flux flow should appear in order to obtain a negative contribution to the Hall voltage. Hagen *et al.*[4] propose that the upstream originates from a general drag force which should be added to the equation of motion for the flux line. Wang and Ting[5] suggest that in a clean superconductor, with inhomogeneities, the remnant pinning force can induce the upstream. While their theory can qualitatively explain all the essential features of ρ_{xy}, it is still quite controversial. Vinokur *et al.*[6] argue that the pinning force is important for the flux motion. They find that the scaling of ρ_{xy} with ρ_{xx} is a general feature for disorder-dominated flux motion in superconductors. They assume that the sign reversal has no relation with the pinning effect. Dorsey[7] and Kopnin, Ivlev, and Katatsky[8] consider the sign reversal from another point of view. They modify the time-dependent Ginzburg-Landau equation (TDGL) by including an additional Hall term and assuming an imaginary component of the relaxation time for the order parameter which depends on details of the electronic band structure of the material. In the framework of this model, they conclude that the Hall conductivity σ_{xy} is induced by both the motion of the flux vortices and the motion of quasiparticles in the regions outside the vortex cores. Similar conclusions are obtained by Geshkenbein and Larkin.[9] Thermoelectric effects (namely Seebeck and Ettingshausen effects) are also considered to be important in the Hall effect, though the amplitude of the thermoelectric effect is usually one order of magnitude smaller than that required to induce the sign reversal of ρ_{xy}.[10]

Studies of the Hall effect anomalies in the mixed state of high-T_c materials have up to now been performed mainly on single crystals and thin films. In this paper, we report measurements of the temperature and field dependence of ρ_{xx} and ρ_{xy} in a $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (YBCO/PBCO) multilayer in the mixed state. In this system the scaling behavior $\rho_{xy} \propto \rho_{xx}^2$ is found to be valid in the low-field region. A clear correlation between the flux motion and the sign reversal of Hall resistivity is obtained. The Hall conductivity σ_{xy} can be described by the superposition of the motion of quasiparticles and vortices. This description is consistent with the theoretical prediction based on TDGL theory.

II. EXPERIMENTAL

The c-axis-oriented $[YBa_2Cu_3O_7(72\ \text{Å})/PrBa_2Cu_3O_7(12\ \text{Å})]_{25}$ multilayer was fabricated by *in situ* dc sputtering. For more details of the film preparation we refer readers to Ref. 12. The sample was photolithographically patterned into an eight-lead configuration with one pair of contact pads for the current, one pair for the transverse (ρ_{xx}) and two pairs for the longitudinal resistivities (ρ_{xy}). The width of the stripe for the ρ_{xy} measurements was 100 μm. Using Ag dots deposited onto the contact pads, and Au wires pressed onto the silver dots by indium, the resulting contact resistance was usually below 1 Ω. A standard low-frequency ac lock-in technique was used to measure ρ_{xx} and ρ_{xy} simultaneously with the help of a Keithley 705 scanner. Hall resistivity ρ_{xy} was deduced from the asymmetric part of the transverse voltage V_{xy} under the magnetic-field reversal. The magnetic field generated by 15-T Oxford superconducting magnet, was applied parallel to the c axis of the film and perpendicular to the ac current. The current used in the measurements was 10 μA, corresponding to a current density of 28 A/cm^2. The temperature stability was better than 0.01 K during the measurements. Since the PBCO layers are insulating at low tem-

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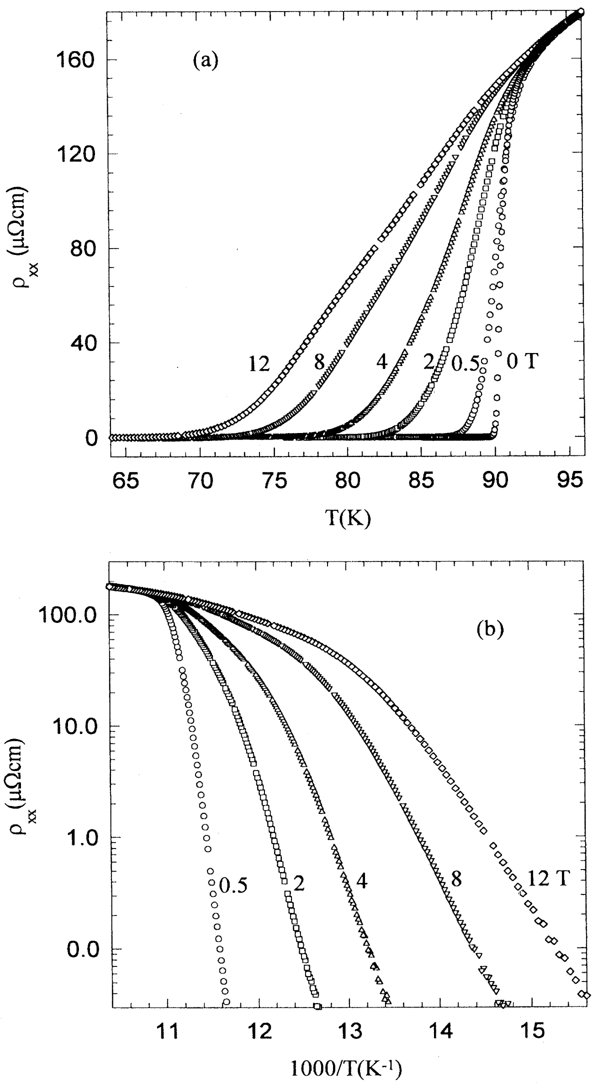


FIG. 1. (a) The temperature dependence of the electrical resistivity for $[YBa_2Cu_3O_7(72\ Å)/PrBa_2Cu_3O_7(12\ Å)]_{25}$ multilayer in different perpendicular applied magnetic fields. (b) The Arrhenius plot of (a) which reveals the TAFF behaviors.

perature, we calculated the longitudinal and Hall resistivity of the sample by using the total thickness of YBCO layers in the multilayer.

Figure 1(a) shows the temperature dependence of ρ_{xx} measured in various perpendicular magnetic fields. Figure 1(b), which is the Arrhenius plot of Fig. 1(a), clearly shows that the lower part of $\rho_{xx}(T)$ exhibits a thermally activated flux-flow (TAFF) behavior. The activation energies extracted from the slopes of $\ln\rho_{xx}$ vs $1/T$ plots are of the order of 10^4 K which is comparable with those measured on epitaxial YBCO thin films. Figure 2(a) shows $\rho_{xy}(T)$ measured at various fields. Above $T_c \approx 92$ K, ρ_{xy} is proportional to the magnetic field, that is, the Hall coefficient R_H is nearly field independent [see inset in Fig. 2(a)]. As the temperature decreases below T_c, ρ_{xy} falls sharply, and even becomes negative until it gradually goes to zero. In high fields [see the curve for $H=12$ T in Fig. 2(a)], the sign reversal in ρ_{xy} disappears. A careful comparison between Figs. 1(a) and 2(a) shows that a finite Hall resistivity ρ_{xy} appears at temperatures lower than those necessary to observe the onset of finite longitudinal resistivity ρ_{xx}.

Figures 3(a) and 3(b) show the field dependence of ρ_{xx} and ρ_{xy}, respectively, at different temperatures. Since we do not find any evidence of a linear field dependence of ρ_{xx}, the Bardeen-Stephen flux-flow model cannot be applied here, i.e., $\rho_{xx}=\rho_n(H/H_{c2})$, ρ_n being the normal-state resistivity. In Fig. 3(b), we can see that at a certain temperature below T_c, when the field grows above a threshold field H_t, ρ_{xy} first appears as negative. In higher fields $H=H_m$, ρ_{xy} reaches a minimum, then ρ_{xy} starts to increase, and in a certain field H_0, a sign reversal of ρ_{xy} is observed [see Fig. 3(b) for the definition of H_t, H_m, and H_0]. Both H_t and H_0 increase as temperature decreases. Similar to the data in Figs. 1 and 2, we can also find some retardation between the onsets of ρ_{xy} and ρ_{xx}.

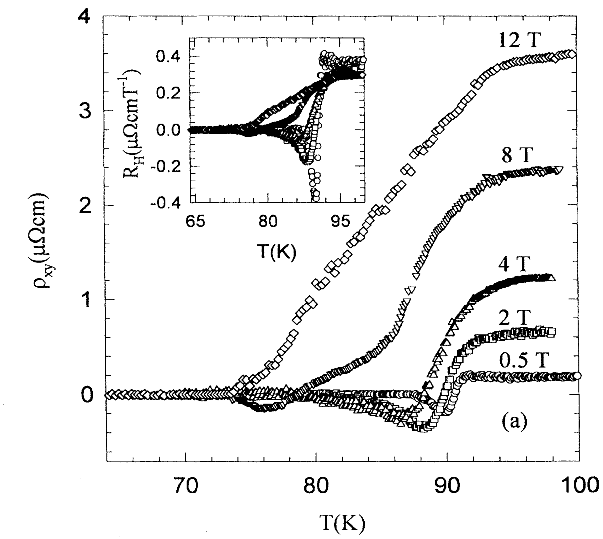
In order to see if there is a correlation between ρ_{xy} and ρ_{xx}, the absolute value of ρ_{xy} vs ρ_{xx} measured at several temperatures is plotted in a log-log scale as shown in Fig. 4. The plot shows a straight line with a slope of about 2 between the fields H_t and H_m. This indicates that ρ_{xy} is proportional to ρ_{xx}^2. Such scaling relations have been reported previously by several groups.[1,13] To further probe the validity of the $\rho_{xy} \propto \rho_{xx}^2$ relation, we compare the temperature dependence of ρ_{xy} [Fig. 2(a)] with the temperature dependence of $d\rho_{xx}/dT$[Fig. 2(b)] which can be used as a measure of the flux-flow contribution. We see that the temperature T_m, at which ρ_{xy} shows a minimum, corresponds to the temperature at which the maximum in the $d\rho_{xx}/dT$ vs T curve is observed. The latter implies that the vortices have the highest mobility at T_m. Below T_m, $d\rho_{xx}/dT$ becomes smaller as the temperature decreases and the pinning effects start to dominate. An analysis of the "apparent activation energy" $|d\ \ln\rho_{xx}/d(1/T)|$ vs T [Fig. 2(c)] shows the similar behavior. Below T_m, $|d\ln\rho_{xx}/d(1/T)|$ is increasing very fast. Such kind of a relation between pinning and Hall sign reversal has also been observed in $Bi_2Sr_2CaCu_2O_{8+x}$ thin films.[14]

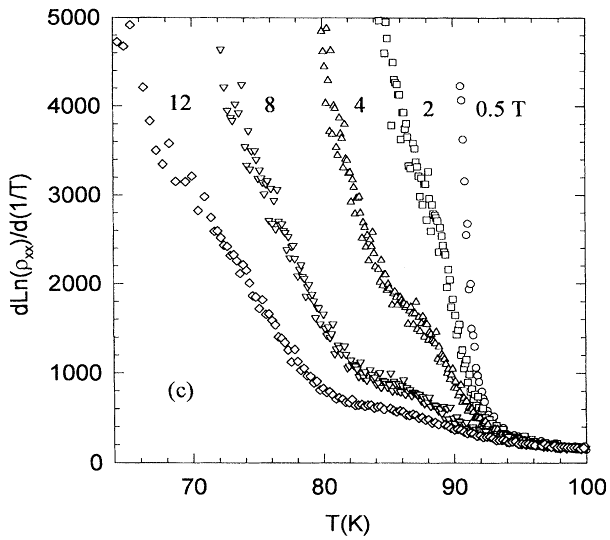
These results can be successfully interpreted if one assumes that (i) the dissipations in the transverse and longitudinal directions are strongly correlated due to the flux motion, and (ii) the sign reversal is not a direct consequence of the pinning effect since our results suggest that the enhanced pinning leads to smaller negative values of ρ_{xy}. This is consistent with the observations of Budhani, Liou, and Cai[15] who measured the Hall resistivities on samples with columnar defects produced by ion irradiation in which they found that the Hall sign anomaly was diminished with increasing defect concentration.

III. DISCUSSION

Our main experimental observations can be understood in the framework of a phenomenological model proposed by Vinokur *et al.*[6] who suggested that in the presence of a pinning force, the equation of motion for a flux line can be written as follows:

$$\eta \mathbf{v}_L + \alpha \mathbf{v}_L \times \mathbf{n} = \Phi_0 \mathbf{j} \times \mathbf{n} + \mathbf{F}_{\text{pin}}. \tag{1}$$





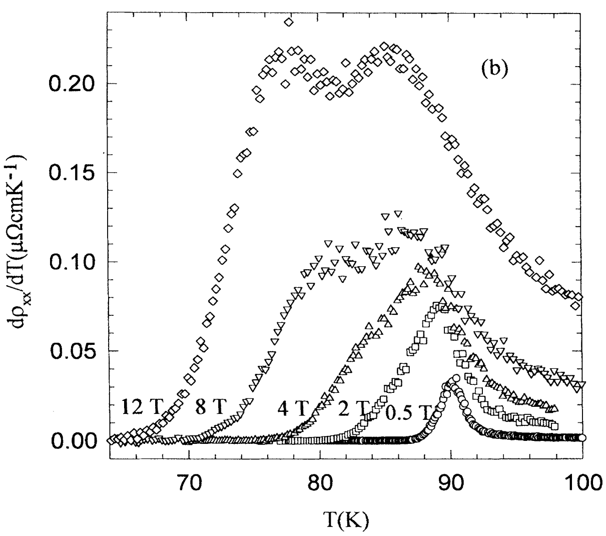


FIG. 2. The temperature dependence of (a) the Hall resistivity ρ_{xy}, (b) $d\rho_{xx}/dT$, and (c) the "apparent activation energy" $|d\ \ln\rho_{xx}/d(1/T)|$ for a $[YBa_2Cu_3O_7(72\ Å)/PrBa_2Cu_3O_7(12\ Å)]_{25}$ multilayer in different perpendicular applied fields. Inset: The corresponding Hall coefficient is calculated from (a).

Here η is the viscous drag coefficient, α is the coefficient related to the Hall effect, $\mathbf{v}_L$ is the flux line velocity, Φ_0 is the flux quantum, and $\mathbf{n}$ is the unit vector in the direction of the magnetic field. According to the authors, the pinning force can be written in the form $\mathbf{F}_{\text{pin}} = -\gamma \mathbf{v}_L$. If the pinning force dominates over the drag force, i.e., $\gamma \gg \eta$, then we obtain from Eq. (1)

$$\rho_{xy} = (\alpha/\Phi_0 H)\rho_{xx}^2 . \tag{2}$$

The sign of ρ_{xy} is determined by the coefficient α. Therefore the scaling behavior is a direct consequence of the pinning-dominated flux dynamics in the mixed state. In contrast to Wang and Ting's result,[5] *the sign reversal has no direct relation with the pinning force*. In the TAFF region where $\rho_{xx} \propto e^{-U/kT}$, $\rho_{xy} \propto \rho_{xx}^2 \propto e^{-2U/kT}$, and $U/kT \gg 1$, the Hall resistivity ρ_{xy} is much smaller than ρ_{xx}. Therefore, it is experimentally more difficult to detect ρ_{xx} than ρ_{xy}, causing a retardation between the onsets of ρ_{xy} and ρ_{xx} (see Fig. 3).

At temperatures close to T_c, the contribution of the normal quasiparticles to the Hall effects may be quite large. This point has been discussed by several authors.[7,8,11] Ferrel[11] has shown that the interaction of thermally excited quasiparticles far outside of the vortex cores with the superfluid can induce a drag force which plays the same roles as that proposed by Hagen *et al.*[4] The appealing results obtained by Dorsey[7] and by Kopnin, Ivlev, and Kalatsky[8] demonstrate that it is better to understand the Hall effect in terms of σ_{xy}. In the flux-flow region, there are two contributions to σ_{xy}. The first is the contribution σ_{xy}^s from the motion of the magnetic vortices. The second σ_{xy}^n arises from the motion of quasiparticles in the region outside of the vortex cores. Motivated by these results, we can try to obtain these two contributions from our measurements [Fig. 3(b)]. Since $\rho_{xy}^2 \ll \rho_{xx}^2$, we can estimate σ_{xy} as ρ_{xy}/ρ_{xx}^2. First, we shall analyze the asymptotic behavior of σ_{xy}. From Fig. 3 we see that in the high-field limit, where ρ_{xy} increases linearly with the fields, ρ_{xx} is nearly field independent. This means that $\sigma_{xy} \propto H$ in the high fields. On the other hand, in the low-field limit, as shown by Kopnin, Ivlev, and Katatsky,[8] and by Dorsey,[7] $\sigma_{xy} \propto 1/H$. Therefore σ_{xy} can be approximated by the superposition of the two terms

$$\sigma_{xy} = C_1/H + C_2 H, \tag{3}$$

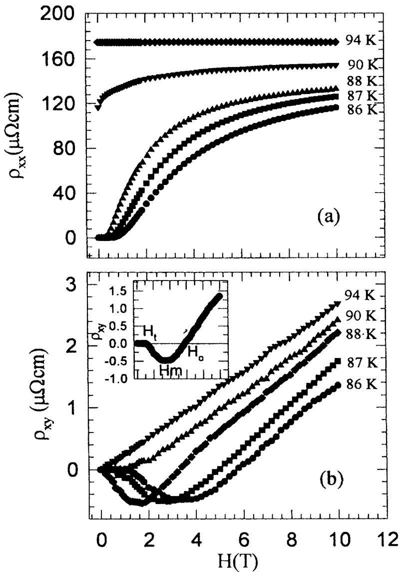


FIG. 3. The field dependence of (a) ρ_{xx} and (b) ρ_{xy} for a $[YBa_2Cu_3O_7(72\ Å)/PrBa_2Cu_3O_7(12\ Å)]_{25}$ multilayer at different temperatures. The inset shows the definitions of H_t, H_0, and H_m.

where C_1 and C_2 are two temperature-dependent coefficients depending on the electronic band structure.[7,8] If C_1 and C_2 have opposite signs, then σ_{xy} can change sign with variations in temperature or magnetic field.

We have used Eq. (3) to fit our experimental data (Fig. 3). In order to simplify the fitting procedure, we multiply both sides of Eq. (3) by H, and plot $\sigma_{xy}H$ vs H^2 on a linear scale (Fig. 5). As is clearly seen from Fig. 5, these plots indeed reveal linear dependences of $\sigma_{xy}H$ upon H^2. The slopes of the plots give the coefficient C_2, while the intercepts give C_1. It turns out that C_1 and C_2 have opposite signs, as anticipated. The temperature dependences of C_1 and C_2 are

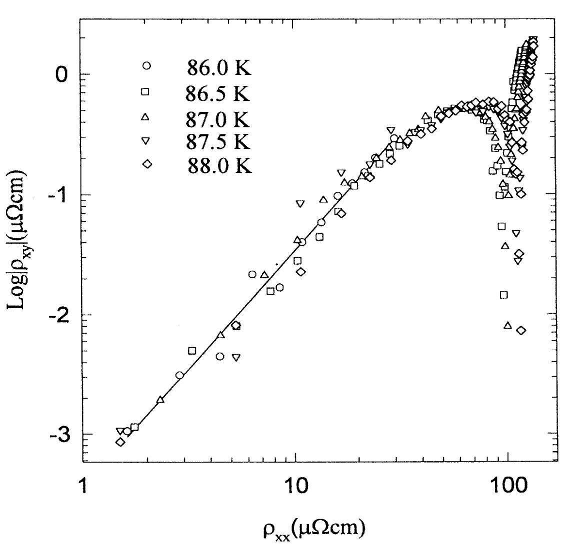


FIG. 4. The log-log plots of ρ_{xy} vs ρ_{xx} dependences at different temperatures.

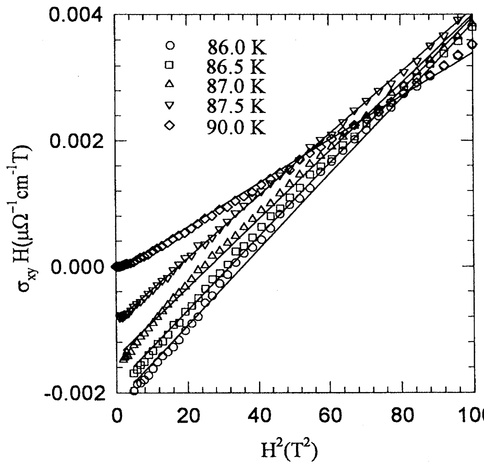


FIG. 5. $\sigma_{xy}H$ vs H^2 for a $[YBa_2Cu_3O_7(72\ Å)/PrBa_2Cu_3O_7(12\ Å)]_{25}$ multilayer at different temperatures. The open symbols are experimental data. The solid lines are the best fits with Eq. (3) in the text.

shown in Fig. 6. We found C_1 is negative and proportional to ε^2, where $\varepsilon=(T_c-T)/T_c$, and $T_c=92.6$ K is the mean-field transition temperature which is taken as the temperature at which $[d\rho_{xx}/dT]_{H=0}$ shows a maximum. The coefficient C_2 is positive and it decreases linearly with temperature.

A similar decomposition of σ_{xy} has also been found recently by several groups. Samoilov, Ivanov, and Johansson[16] have found that in the low fields $\sigma_{xy} \propto 1/H$ while Harris, Ong, and Yan,[17] and Ginsberg and Manson[18] have reported $\sigma_{xy} \propto 1/H$ in the low-field region and $\propto H$ in the high-field limit. Thus, we conclude that indeed both the motion of vortices and quasiparticles contribute to the Hall conductivity. While the theoretical prediction of Dorsey[7] agrees well with the work of Samoilov, Ivanov, and Johansson[16] whose results

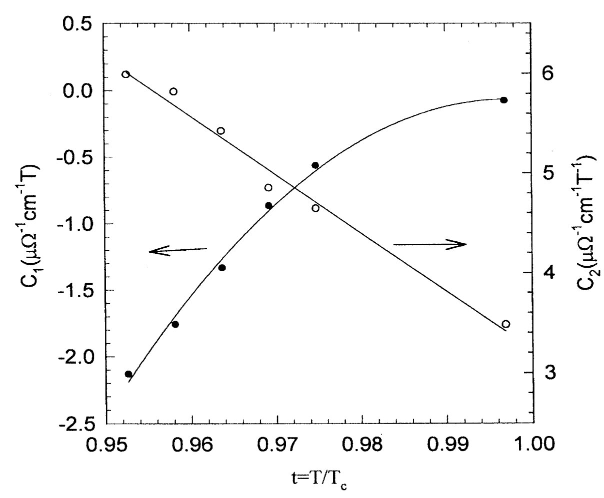


FIG. 6. The temperature dependence C_1 (filled circles) which is obtained from the intercept of the solid lines shown in Fig. 5 with $H=0$ axis, and the temperature dependence of C_2 which are obtained from the slope of the solid lines in Fig. 5. The solid lines are fits with $C_1 \propto (1-T/T_c)^2$ and $C_2(1-T/T_c)$, respectively, with $T_c=92.08$ K.

were obtained in relatively low fields, it shows some discrepancy with our results in the high fields. This can be explained in the following way. Since the model we mentioned above is based on the equation of motion for single vortex, no interaction between flux lines is included. Therefore, it should work better in the low-field region. Thus, an extension of this theory to include the effects of pinning and flux interactions is strongly suggested.

We notice that when Kunchur *et al.*[19] performed the Hall-effect measurement in the free flux-flow regime, they found an additivity of the Hall angle instead of an additivity of σ_{xy} found here and by other groups.[18,20,21] Their results also suggest the importance of the quasiparticles in the Hall sign reversal.

If the results obtained from the TDGL are correct, then a negative Hall angle will appear for the quasiparticle spectrum with a positive energy derivative of the density of state averaged over the Fermi surface.[8] This can easily happen in a superconductor with a complicated Fermi surface. Therefore, the sign reversal will depend crucially on the shape of the Fermi surface and the position of the Fermi level. Recently there appeared some reports about the relationship between the sign reversal and l/ξ_0, where l is the mean free path and ξ_0 is the BCS coherence length.[22,23] It has been found that the sign reversal is easily observed in samples with l of the same order as ξ_0. Correlation between the normal-state resistivity and sign reversal has also been reported.[24,25] Using a free-electron approximation, we can make a simple estimation of l of our sample from the normal-state resistivity and the carrier density. With $\xi_0 \approx 12$ Å, we find $l/\xi_0 \approx 1.4$, this value falls into the region where Hagen *et al.*[22] have found the pronounced sign reversal.

An alternative explanation of the sign reversal can be understood in a phenomenological way as shown by Feigel'man *et al.*[26] From the momentum conservation between the superfluid and crystal lattice, we can get the following equation:

$$\omega_0 \tau \mathbf{n} \times (\mathbf{v}_L - \mathbf{v}_c) = \mathbf{v}_c , \tag{4}$$

where $\mathbf{v}_c$ is the velocity of the normal carriers inside the core in the laboratory frame, $\omega_0 = \hbar/2r_c^2 m$, $r_c \approx \xi$ being the radius of the vortex core, and τ the transport time. In the mixed state, the carrier density inside the core (n_0) and far outside the core (n_∞) may be different. Therefore, the product $n_0 e \mathbf{v}_L$ is not equal to j_T, the transport current density. From the current conservation we have $n_0 e(\mathbf{v}_c - \mathbf{v}_L) = \mathbf{j}_T - \mathbf{n}_\infty e \mathbf{v}_L$. Thus, the flux-flow Hall conductivity is given by

$$\sigma_{xy} = \frac{n_0 e c}{B} \frac{(\omega_0 \tau)^2}{1 + (\omega_0 \tau)^2} - \frac{\delta n e c}{B} , \tag{5}$$

where m is the effective mass, $\delta n = n_0 - \mathbf{n}_\infty$ is the difference between the carrier density on the axis of the vortex core and that far outside the core. An estimate for δn is obtained from $\delta n / n = \mathrm{sign}(\delta n)(\Delta / E_F)^2$, where Δ is the superconducting energy gap and E_F the Fermi energy. Since $\omega_0 = \Delta^2 / E_F \ll \tau^{-1}$, then from Eq. (4) we have

$$\sigma_{xy} = \frac{n_0 e c}{B} \frac{\Delta^2}{E_F^2} [(\Delta \tau)^2 - \mathrm{sign}(\delta n)]. \tag{6}$$

In the dirty limit, $\Delta \tau < 1$ and sign reversal is possible if $\delta n > 0$. Again we see a direct relation between sign reversal and the electronic structure of the materials.

IV. CONCLUSIONS

In summary, our experimental data on the field and temperature dependence of ρ_{xx} and ρ_{xy} in our YBCO/PBCO multilayer shows that ρ_{xx} and ρ_{xy} exhibits a scaling behavior in the pinning dominated vortex dynamics region. The increase of pinning at lower T diminishes the negative ρ_{xy}. We have found that the σ_{xy} behavior can be described by the superposition of two terms which are related to the dissipation inside the vortex core and that from the movement of quasiparticles far outside of vortex core. Our results are qualitatively consistent with the prediction derived from TDGL theory.

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