RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 43, NUMBER 7 1 MARCH 1991

Flux-flow Hall effect in superconducting $Tl_2Ba_2CaCu_2O_8$ films

S. J. Hagen, C. J. Lobb, and R. L. Greene*
Center for Superconductivity Research, Department of Physics and Astronomy,
University of Maryland, College Park, Maryland 20742

M. Eddy
Superconductor Technologies Incorporated, 460 Ward Drive, Suite F, Santa Barbara, California 93111

(Received 28 November 1990)

In both high-T_c and low-T_c superconductors, the Hall effect in the mixed state often shows a sign reversal below T_c that contradicts standard theories for flux-vortex motion. We have measured the mixed-state Hall effect in high-quality superconducting films of $Tl_2Ba_2CaCu_2O_8$, and find that the Hall angle α below T_c consists of two components: A field-independent component exhibits a complicated temperature dependence, including a sign change near T_c, while a second component with very weak temperature dependence is linear in field and resembles the normal-state Hall angle. The field independence of the sign-reversing component is evidence for vortex motion, and can be understood in terms of simple drag forces acting on vortices.

The Hall effect in the mixed state has been a persistent problem in the understanding of flux motion in superconductors. Early experiments[1] on low-T_c superconductors found a variety of behaviors for the Hall angle $\alpha = \tan^{-1}(\rho_{xy}/\rho_{xx})$, including a sign reversal near T_c that could not be understood within existing theories of vortex motion. Recent measurements[2,3] on high-T_c superconductors have consistently shown α changing from positive to negative below T_c in ceramic, single-crystal, and epitaxial film samples, and establish that this phenomenon is an intrinsic property of these superconductors. However, the origin of this effect remains unclear. Some authors have proposed that sign reversal of α in $YBa_2Cu_3O_7$ may result not from flux motion but from superconducting fluctuations[4] or two-band effects.[5] We have argued[3] that the presence of sign reversal in such diverse superconductors as $YBa_2Cu_3O_7$ and Nb instead suggests that general properties of vortex motion are responsible.

We report here a study of the mixed-state Hall effect in epitaxial films of the high-T_c superconductor $Tl_2Ba_2CaCu_2O_8$, in which the behavior of the Hall angle below T_c provides very strong support for a flux-motion interpretation. Below T_c we find the Hall angle contains a sign-reversing component that is remarkably independent of field from $B \sim 50$ kG down to $B \sim 2$ kG. It also contains a component that is linear in field and nearly temperature independent, indicating a normal-electron contribution persisting to low temperatures.

$Tl_2Ba_2CaCu_2O_8$ is especially suitable for vortex-motion studies because the pinning of flux vortices is known[6] to be very weak within 20–30 K of T_c in magnetic fields of 10–50 kG. We measured the Hall resistance r_{xy} and sheet resistance r_{xx} of thin films of c-axis-oriented $Tl_2Ba_2CaCu_2O_8$ (on a $LaAlO_3$ substrate) in magnetic fields up to 50 kG perpendicular to the film. The films (~ 1 μm thick) were prepared by laser ablation from a single target followed by post-deposition heat processing, and possess critical currents $\sim 10^6$ A/cm^2 at 77 K and $T_c \approx 104$ K (resistive midpoint). After patterning the sample into a 4×0.050 mm^2, eight-lead strip (inset to Fig. 1), we measured r_{xx} and r_{xy} at ac densities $J \sim 10^3$ A/cm^2. Both r_{xx} and r_{xy} were Ohmic at these currents. We obtained the Hall resistance r_{xy} from the transverse resistance by subtracting the positive and negative magnetic-field data.

Figure 1 shows r_{xx} and r_{xy} versus temperature near T_c for magnetic fields up to 50 kG. While the pronounced

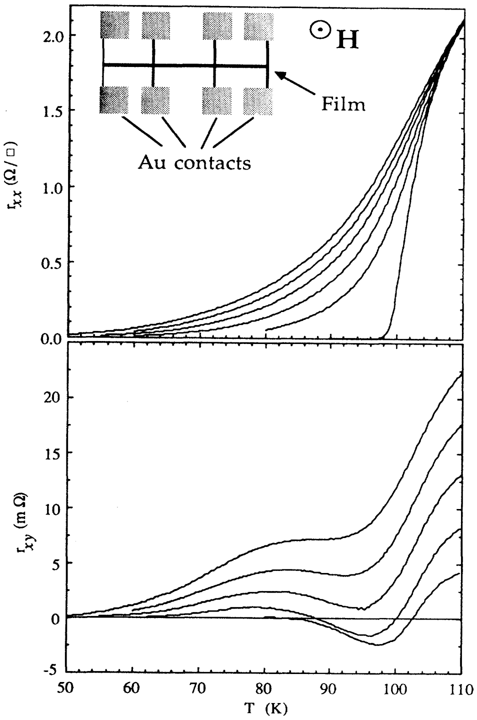

FIG. 1. (Upper) sheet resistance r_{xx} and (lower) Hall resistance r_{xy} vs temperature. Fields from top to bottom are 50, 40, 30, 20, and 10 kG. Upper plot also includes data at zero field. Inset: Patterning of film sample for Hall measurement.

broadening of the r_{xx} transition in a magnetic field has been discussed by other authors,[7] the field and temperature dependence of r_{xy} is also quite remarkable. At $T > T_c$ r_{xy} is positive, linear in field, and only weakly temperature dependent. However, r_{xy} below T_c shows a complicated field and temperature dependence, with a negative minimum appearing near $T = 95$ K for fields $B < \sim 30$ kG. Higher fields drive r_{xy} positive, although the minimum near $T = 95$ K persists to $B > 50$ kG.

A plot of $\tan\alpha$ vs T (Fig. 2) shows a suggestive feature of the data: Hall-angle measurements at different fields produce similar curves displaced vertically from each other. Figure 2 (upper) shows data at high fields, where the regular displacement between curves reflects a component of $\tan\alpha$ linear in field and nearly temperature independent. Figure 2 (lower) shows $\tan\alpha$ at smaller fields (for a different sample), where the experimental data converge on a field-independent but sign-reversing curve. Inspection of Fig. 2, as well as a numerical subtraction of the data, reveal that the Hall angle contains two components: a temperature-sensitive but field-independent part with a negative minimum near 95 K and broad maximum near 70 K, and a second part that is only weakly temperature dependent but nearly linear in field. That is, the Hall angle below T_c obeys an empirical relationship

$$\alpha(T,H) \approx \beta_0(T)H + \alpha_1(T)\,, \qquad (1)$$

where $\beta_0(T)$ is nearly constant and resembles its normal-state value (i.e., the Hall mobility) in sign and magnitude, and $\alpha_1(T)$ reverses sign below T_c.

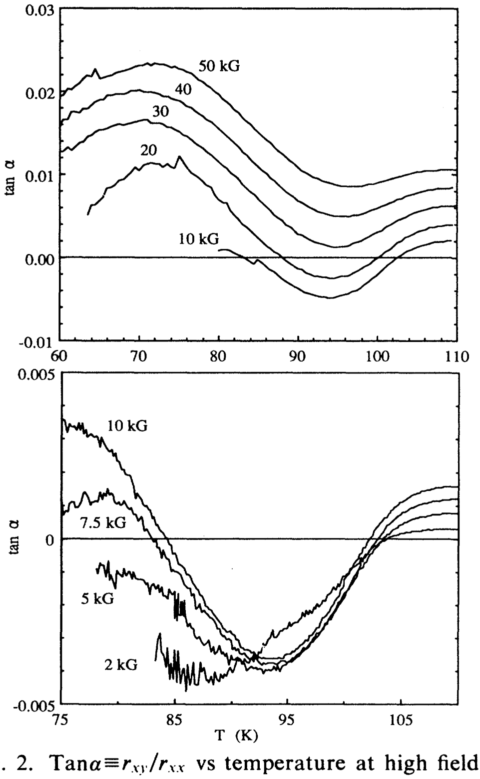

FIG. 2. $\tan\alpha \equiv r_{xy}/r_{xx}$ vs temperature at high fields (upper) and low fields (lower). A field-independent component of $\tan\alpha$ is clearly visible in both plots.

Josephson showed[8] that flux-vortex motion at a velocity $\mathbf{v}_L$ in a type-II superconductor generates a perpendicular dc electric field $\mathbf{E}$ according to

$$\mathbf{E} = -\mathbf{v}_L \times (\mu\mathbf{H})\,. \qquad (2)$$

Dissipative electric fields (i.e., parallel to a transport current $\mathbf{j}$) therefore indicate vortex motion in the direction of $\mathbf{j}\times\mathbf{H}$, while Hall voltages arise from motion parallel to $\mathbf{j}$. For our experimental geometry, where $\mathbf{v}_L$ and $\mathbf{j}$ lie in a plane perpendicular to $\mathbf{H}$, the Hall angle is then the angle between $\mathbf{v}_L$ and $\mathbf{j}\times\mathbf{H}$. If vortex motion is driven by a current-induced force $\mathbf{F}$ and opposed by a frictional force $\mathbf{f}$, the velocity $\mathbf{v}_L$ is determined by the steady-state condition that the net force $\mathbf{F}+\mathbf{f}=\mathbf{0}$. If the forces are not field dependent and the vortices do not interact strongly, then $\mathbf{v}_L$ is independent of the density of vortices, and the Hall angle is independent of field.

However, the nature of the forces $\mathbf{F}$ and $\mathbf{f}$ in superconductors has been a subject of controversy. Bardeen and Stephen[9] (BS) argued that a transport current $\mathbf{j}$ drives flux motion by the "Lorentz" force $\mathbf{F} = n_s e\phi_0 \mathbf{v}_s \times \mathbf{k}$ acting per unit length of vortex line, where n_s is the density of superconducting electrons, $\mathbf{k} = \mathbf{H}/|H|$, and $\mathbf{v}_s = \mathbf{j}/n_s e$. The motion of the vortex and its associated superfluid velocity field requires acceleration of superfluid and, through the London equations, generates electric fields in the vortex core. The resulting Ohmic losses produce a viscous drag force $f = -\eta(T)v_L$ opposing the Lorentz force.

Noziéres and Vinen[10] (NV) argued that the correct driving force on a vortex in a superconductor is the Magnus force $\mathbf{F} = n_s e\phi_0(\mathbf{v}_s - \mathbf{v}_L)\times\mathbf{k}$. They proposed a frictional force of the form $\mathbf{f} = -a(T)\mathbf{v}_s$ to represent the loss of supercurrent momentum as electrons passing through the vortex cores dissipate energy into the crystal lattice.

But while both the BS and NV models generated flux-flow resistances in reasonable agreement with experiment (i.e., $E_x/j_x \sim H$), these models proved incapable of explaining the unusual Hall effect near T_c in many superconductors.[11] The NV and BS Hall angles (predicting $\tan\alpha = \text{const}$ and $\tan\alpha \sim H$, respectively) are of the same sign and similar magnitude as in the normal state, while a range of behavior was observed experimentally, including sign reversal below T_c in Nb, V, and Pb-In alloys.[1,3] More recently, sign reversal of $\tan\alpha$ was also observed in the high-temperature superconductors[2,3] $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$. Hirsch and Marsiglio[5] have proposed a two-band model for the sign reversal in $YBa_2Cu_3O_7$, while Aronov and Hikami[4] have argued that skew-scattering fluctuations could account for it, but the presence of this effect in so many different superconductors (now including $Tl_2Ba_2CaCu_2O_8$) suggests instead that it reflects general properties of vortex motion in superconductors.

We recently argued[3] that sign reversal of the Hall effect in $YBa_2Cu_3O_7$ can be understood within such a vortex-motion model, and that it indicates vortex motion with a velocity component antiparallel to the transport current [through (2)]. Measurements[12] of the Nernst effect in the mixed state support this picture by verifying that the field and temperature regimes of $\alpha < 0$ in $YBa_2Cu_3O_7$ are characterized by extensive flux flow. The field-independent component $\alpha_1(T)$ in Fig. 2 offers strong additional evidence for a flux-motion model, since α can then be independent of the vortex density.

We show here how a modified NV model can account qualitatively for this behavior and produce the field-independent Hall angle $\alpha_1(T)$ seen in $Tl_2Ba_2CaCu_2O_8$. NV argued on very general grounds that vortex motion in a superconductor is driven by the Magnus force, not the Lorentz force. However, the opposing friction force $\mathbf{f}$, which fixes the direction of vortex motion, is more model dependent and difficult to calculate. It is not actually clear that the NV frictional force $\mathbf{f} = -a\mathbf{v}_s$ and the BS damping $\mathbf{f} = -\eta\mathbf{v}_L$ even describe the same dissipative mechanism. Certainly the NV friction cannot be considered complete near T_c, since NV is a $T=0$ theory. We argue that because the motion of flux vortices is intrinsically dissipative, a viscous force of the BS type directly opposing the motion should exist. That is, we propose that friction terms of *both* types should be included in the NV model at finite temperature. In that case, vortex motion in a superconductor obeys

$$\mathbf{F}_{\text{Magnus}} - a\mathbf{v}_s - \eta\mathbf{v}_L = 0 \,, \tag{3}$$

where the NV model is extended to include an additional damping term of the BS form. Solution of this equation gives the Hall angle

$$\tan\alpha = \frac{(n_s e\phi_0)^2 - \eta a}{n_s e\phi_0(\eta + a)} \,. \tag{4}$$

This Hall angle is generally temperature dependent but is field dependent only to the extent that η, n_s, and a are field dependent. In the BS and NV theories, these parameters are given by $\eta \approx \phi_0\mu_0 H_{c2}(T)\sigma_n(T)$, $a \approx n_s ne^2\phi_0/(2\mu_0 H_{c2}(T)\sigma_n(T))$, where $\sigma_n(T)$ is the normal-state conductivity and n is the normal-state carrier density. We note that Eq. (4) predicts a negative Hall angle if $\eta a > (n_s e\phi_0)^2$. For the BS and NV values of a and η, this corresponds to $n_s < n/2$. Because the NV theory was not developed for $T \sim T_c$, it is inappropriate simply to insert these values into (4), but we note that the result is consistent with the observed sign reversal near T_c, and that the magnitude of the Hall angle predicted below T_c is close to the observed value of $\alpha_1(T)$. [This rough numerical consistency makes the drag forces in Eq. (3) more reasonable than those we proposed earlier in Ref. 3.]

Therefore the field-independent part observed in α can be qualitatively understood if the Magnus force is opposed by both NV and BS damping forces. These forces exist even in the limit of very small fields; they describe the interaction of single vortices with the applied transport current, the crystal lattice, and the dissipative effects due to normal carriers. The second, field-dependent component of α in (1) could arise from the Hall effect of normal electrons persisting in, for example, the vortex cores. Normal currents in the cores are deflected by the local value of the magnetic field, as in the normal state, giving rise to a Hall electric field proportional to H. This additional field will add an extra component to $\mathbf{v}_L$ parallel to $\mathbf{j}$, through (2). This mechanism was originally proposed by BS as the origin of the *entire* Hall effect in a superconductor.

The weak flux pinning in $Tl_2Ba_2CaCu_2O_8$ makes this system ideal for studying the mixed-state Hall effect. Despite a complicated field and temperature dependence, the Hall angle in this system consists of two components that can be understood in simple models. A field-independent component reverses sign upon entering the mixed state, indicating a component of vortex velocity antiparallel to the superfluid transport current. This can be understood as NV flux motion if the damping force is generalized to include an additional viscosity term. Sign reversal of the Hall angle in the mixed state therefore points to general properties of flux-flow dynamics, rather than specific band-structure or sample-dependent properties. It would be interesting to look for the same field-independent Hall angle in other superconductors known to have very weak pinning near T_c. In addition to this temperature-dependent part of the Hall angle there is also a component that is weakly temperature dependent but linear in field; this may indicate residual normal charge carriers, perhaps occurring in the vortex cores. The behavior of α in this system clearly demonstrates the need for more theoretical work on the vortex-motion problem.

This research was supported in part by the Electric Power Research Institute.

---

[*] Also at IBM Research Division, Yorktown Heights, NY 10598.

[1] C. H. Weijsenfeld, Phys. Lett. **28A**, 362 (1968); H. Van Beelen *et al.*, Physics **36**, 241 (1967); N. Usui, T. Ogasawara, K. Yasukochi, and S. Tomoda, J. Phys. Soc. Jpn. **27**, 574 (1969).

[2] Y. Iye, S. Nakamura, and T. Tamegai, Physica C **159**, 616 (1989); S. N. Artemenko, I. G. Gorlova, and Y. I. Latyshev, Phys. Lett. A **138**, 428 (1989); K. C. Woo, K. E. Gray, R. T. Kampwirth, and J. H. Kang, Physica C **162–164**, 1011 (1989); T. R. Chien, N. P. Ong, and Z. Z. Wang (unpublished); M. Galffy and E. Zirngiebl, Solid State Commun. **68**, 929 (1988); L. Forró and A. Hamzic, *ibid.* **71**, 1099 (1989).

[3] S. J. Hagen, C. J. Lobb, R. L. Greene, M. G. Forrester, and J. H. Kang, Phys. Rev. B **41**, 11 630 (1990).

[4] A. G. Aronov and S. Hikami, Phys. Rev. B **41**, 9548 (1990).

[5] J. E. Hirsch and F. Marsiglio, Phys. Rev. B **43**, 424 (1991).

[6] For a recent review see *Proceedings of the International Conference on Materials and Mechanisms of Superconductivity-High-Temperature Superconductors II, Stanford, CA, 1989* [Physica C **162–164** (1989)].

[7] D. H. Kim, K. E. Gray, R. T. Kampwirth, and D. M. McKay, Phys. Rev. B **42**, 6249 (1990). These authors argued that the resistive broadening is due to Josephson-coupling effects rather than flux motion; however, we believe their model would incorrectly give $r_{xy} = 0$.

[8] B. Josephson, Phys. Lett. **16**, 242 (1965).

[9] J. Bardeen and M. J. Stephen, Phys. Rev. **140**, A1197 (1965).

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

[11] We note that T. W. Jing and N. P. Ong, Phys. Rev. B **42**, 10781 (1990), recently found some support for the NV model in the Hall effect of low-T_c $NbSe_2$.

[12] S. J. Hagen, C. J. Lobb, R. L. Greene, M. G. Forrester, and J. Talvacchio, Phys. Rev. B **42**, 6777 (1990).