Pinning and the mixed-state thermomagnetic transport properties of $YBa_2Cu_3O_{7-\delta}$

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We have studied the role of pinning in the mixed-state thermomagnetic transport properties of $YBa_2Cu_3O_{7-\delta}$. We demonstrate the pinning independence of the transport entropy S_ϕ, and its consequent scaling within an anisotropic mass model. Due to the anisotropy of $YBa_2Cu_3O_{7-\delta}$ the extrinsic pinning strength effectively decreases as we rotate the magnetic field into the ab plane. The Nernst ($E_y/\nabla_x T$) and Seebeck ($E_x/\nabla_x T$) effects are enhanced as we reduce the effective pinning, yet the transport entropy $S_\phi \propto (E_y/\nabla_x T)/\rho_{xx}$, the ratio of the Nernst and Seebeck signals, and the ratio of Seebeck and longitudinal resistivity ρ_{xx} are *unchanged*, similar to the pinning independence observed for the Hall conductivity σ_{xy}. These results can be explained within a simple phenomenological model of vortex dynamics. [S0163-1829(96)50138-4]

There has been considerable effort both experimentally and theoretically to understand how vortex motion is affected by flux pinning.[1] Much of the recent interest in flux dynamics has been devoted to, and motivated by, the experimental observation of an anomalous sign change of the mixed-state Hall effect.[2] The sign change is not explained within conventional models of Hall-effect vortex dynamics, which are calculated in the absence of pinning.[3,4] While some recent phenomenological models of vortex motion have incorporated flux pinning to explain the sign change,[5] Vinokur, Geshkenbein, Feigel'man, and Blatter (VGFB),[6] by contrast, argue that the sign anomaly is not pinning related and, in particular, that the Hall conductivity σ_{xy} should be independent of pinning. This picture is supported by recent experiments demonstrating the pinning independence of σ_{xy} in materials where a sign change occurs.[7–9]

We extend our recent work on the role of pinning in the mixed-state Hall effect[8] to the thermomagnetic regime. In our experiments we apply a temperature gradient $\nabla_x T$ in the ab plane and measure the Nernst and Seebeck effects. We carry out these measurements over a range of magnetic-field orientations, varying the angle θ between the c axis and the field. Within the anisotropic mass model of Blatter, Geshkeinbein, and Larkin,[10] as a result of the anisotropy of $YBa_2Cu_3O_{7-\delta}$ (YBCO) ($\Gamma \cong 40$), the extrinsic pinning effectively decreases with increasing θ. We scale the data in terms of this anisotropic mass model and observe the enhancement of the Nernst and Seebeck effects with increasing angle θ. However, we find the transport entropy $S_\phi \propto (E_y/\nabla_x T)/\rho_{xx}$, as well as the ratio of the Nernst and Seebeck signals, and the ratio of Seebeck and longitudinal resistivity ρ_{xx} are *independent* of angle θ, as observed for the Hall conductivity σ_{xy}.[8]

The YBCO data were collected on two c-axis-oriented $\approx$1000 Å thick films grown by pulsed laser ablation with $T_c = 91$ K. The samples are mounted in a diving board configuration with one end heat sunk to a Cu block and the other end left suspended, as depicted in Fig. 1. A heater is attached to the free end of the film to produce a temperature gradient along its length. Slow ($\sim$10 mHz) square pulses of heater power produce a small oscillating temperature gradient ($\leqslant$2 K/cm) and transverse and longitudinal voltages, which are signal averaged. Two 25 μm chromel-constantan thermocouples measure the temperature gradient, and six calibrated 50 μm Au wires, heat sunk to the Cu base to minimize thermal noise, provide electrical connections to the film. The magnetic field is ramped from high to low fields at both polarities; we define the Nernst voltage as the component of the transverse voltage odd in applied field. We have the capability to vary the field direction with respect to the sample in a vacuum, and we use a magnetic-field insensitive Cernox metal film thermometer for all measurements. We measure the film resistivity ρ_{xx} and Hall resistivity ρ_{xy} in addition to the thermoelectric properties.

To understand flux flow under the influence of a temperature gradient $\boldsymbol{\nabla} T$ we consider a phenomenological model of vortex dynamics that has been addressed by Huebener *et al.*[11] and discussed in detail by Samoliov *et al.*[12] We generalize these discussions by including the effects of pinning, so that the equation of motion for each vortex is given by

$$-S_\phi \boldsymbol{\nabla} T + \phi_0 \frac{Q_n}{\rho_n} \boldsymbol{\nabla} T \times \hat{\mathbf{n}} - \eta \mathbf{v} - \alpha \mathbf{v} \times \hat{\mathbf{n}} - \langle \mathbf{F}_{\rm pin} \rangle = 0, \quad (1)$$

where $-S_\phi \boldsymbol{\nabla} T$ is the thermal force that drives vortices towards the cold end of the sample, S_ϕ is the transport entropy per vortex unit length, the second term is the Lorentz force ($\equiv \phi_0 \mathbf{J}_s \times \hat{\mathbf{n}}$, $\mathbf{J}_s = Q_n \boldsymbol{\nabla} T/\rho_n$ [A/cm^2]) that arises in response

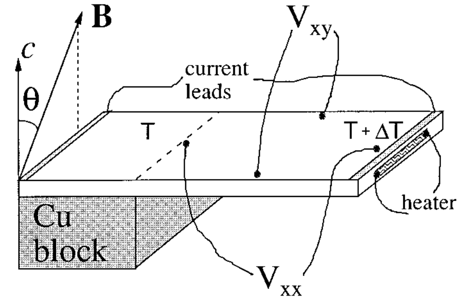

FIG. 1. Experimental arrangement for our thermal transport measurements.

to the normal core thermopower (neglecting the much smaller normal core Nernst and Hall effects),[12] Q_n is the normal state thermoelectric power, ρ_n is the normal state resistivity, $\phi_0=h/2e$ is the flux quantum, $\hat{\mathbf{n}}$ is a unit vector in the direction of the magnetic field, η is the viscous drag coefficient, $\mathbf{v}$ is the average vortex velocity, α is related to the Hall angle in the absence of pinning by $\tan\theta_H=\alpha/\eta$, and $\langle \mathbf{F}_{\text{pin}}\rangle$ is the average pinning force. In discussing the mixed-state Hall effect VGFB argue that the average pinning force can be replaced by a term which, to leading order, is linear in the vortex velocity and independent of field direction.[13] If we generalize this to the thermomagnetic regime, Eq. (1) can be written as

$$-S_\phi \nabla T+\phi_0 \frac{Q_n}{\rho_n} \nabla T\times\hat{\mathbf{n}}-[\eta+\gamma(v)]\mathbf{v}-\alpha\mathbf{v}\times\hat{\mathbf{n}}=\mathbf{0}, \qquad (2)$$

so that pinning has the effect of renormalizing the drag coefficient, $\eta\rightarrow\eta+\gamma(v)$.[14]

The moving vortices generate a spatially averaged electric field according to Josephson's relation $\mathbf{E}=-\mathbf{v}\times\mathbf{B}$,[15] which, together with Eq. (2), allows us to determine the Nernst ($E_y/\nabla_x T$) and Seebeck ($E_x/\nabla_x T$) coefficients, where for convenience the temperature gradient is applied along the x direction. We obtain

$$E_y/\nabla_x T=\frac{B}{\eta+\gamma(v)}(1+\tan^2\theta_H)^{-1}\left[\phi_0 \frac{Q_n}{\rho_n}\tan\theta_H-S_\phi\right] \cong -\frac{S_\phi B}{\eta+\gamma(v)} \qquad (3)$$

and

$$E_x/\nabla_x T=\frac{B}{\eta+\gamma(v)}(1+\tan^2\theta_H)^{-1}\left[S_\phi\tan\theta_H+\phi_0\frac{Q_n}{\rho_n}\right] \cong \frac{\phi_0(Q_n/\rho_n)B}{\eta+\gamma(v)}, \qquad (4)$$

where, in our final expression, we have neglected terms in $\tan\theta_H=\alpha/(\eta+\gamma)$ ($\sim 10^{-2}$–10^{-4}).[8] Equations (3) and (4) imply the Nernst and Seebeck effects should change as pinning is varied, while their ratio, $E_y/E_x=\rho_n S_\phi/\phi_0 Q_n$, should be *independent* of pinning.

Since α determines the sign of the Hall effect,[6] sign changes might be observable in thermomagnetic measurements when $\tan\theta_H$ is large ($\geqslant 1$), and, indeed, there is experimental evidence for Hall angles of this magnitude.[16] In addition, different field and pinning dependences of the Nernst and Seebeck effects should be observable in this regime, as terms are no longer negligible in Eqs. (3) and (4).

The vortex transport entropy S_ϕ is of significant theoretical interest because it reflects the number of quasiparticle states in the core. Theories which estimate S_ϕ do not incorporate pinning,[17,18] thus comparison to experiments has been limited to the field and temperature range where pinning is weak. The standard technique to extract S_ϕ from experiment is to measure the Nernst effect and flux flow resistivity ρ_{xx}, where in the absence of pinning $E_y/\nabla_x T\cong S_\phi B/\eta$, and η is derived from the Lorentz-force relation $\rho_{xx}=\phi_0 B/\eta$.[19] Thus the transport entropy is given by $S_\phi=\phi_0 E_y/(\nabla_x T\rho_{xx}.)$

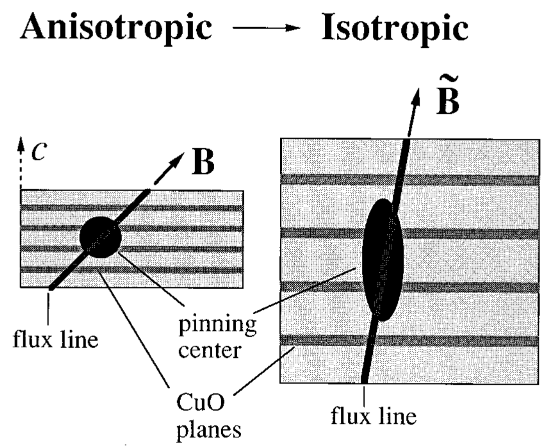

FIG. 2. Depiction of pinning center, flux line, and field in anisotropic and scaled isotropic system based on the models of Ref. 10. The scaling of the field is described in the text.

However, according to VGFB,[6,13] to leading order in the renormalized drag coefficient, ρ_{xx} is given by

$$\rho_{xx}=\frac{\phi_0 B}{\eta+\gamma(v)}, \qquad (5)$$

and should have the same pinning dependence as the Nernst and Seebeck effects. Therefore the vortex transport entropy, $S_\phi=\phi_0 E_y/(\nabla_x T\rho_{xx})$, should be *independent* of pinning.[14] Other quantities such as the ratio of the Seebeck effect to the resistivity ρ_{xx}, $(E_x/\nabla_x T)/\rho_{xx}=Q_n/\rho_n$, should also be unaffected by pinning.[14]

As a test of these results we have varied the pinning strength in YBCO and measured the Nernst and Seebeck effects and resistivity. In Fig. 1 we demonstrate the experimental arrangement we use to carry out this test. Geshkenbein and Larkin[10] argue that pinning by defects is anisotropic, being weaker when the field is in the ab plane. Thus, to vary flux pinning we take advantage of YBCO's anisotropy and the resulting weakening of the extrinsic pinning as the magnetic field is directed toward the ab plane.[8,10] This technique, which we,[8] as well as Harris *et al.*,[7] recently applied to demonstrate the pinning independence of the Hall conductivity σ_{xy}, can also be applied in thermomagnetic measurements.

In Fig. 2 we depict the anisotropy of the pinning, as well as other physical consequences of an anisotropic material. Within the anisotropic mass model of Blatter, Geshkenbein, and Larkin[10] the anisotropic system can be mapped into an isotropic system where, now, the defects are elongated and become columnarlike. As the field is tilted off the c axis in the isotropic system the overlap between the vortex core and the elongated defect decreases, thus increasing the free energy of the pinned vortex system and weakening the effective pinning strength.

We rotate the sample to vary the angle θ between the c axis and the field, while keeping the temperature gradient $\nabla_x T$ (and/or J_x) and field perpendicular to each other. Geshkenbein and Larkin argue[10] that the field should be scaled to $\tilde{H}=H\sqrt{\cos^2\theta+\Gamma^{-1}\sin^2\theta}$, and there is a scaling factor $H_z/\tilde{H}=1/\sqrt{1+\Gamma^{-1}\tan^2\theta}$ for the transverse components of

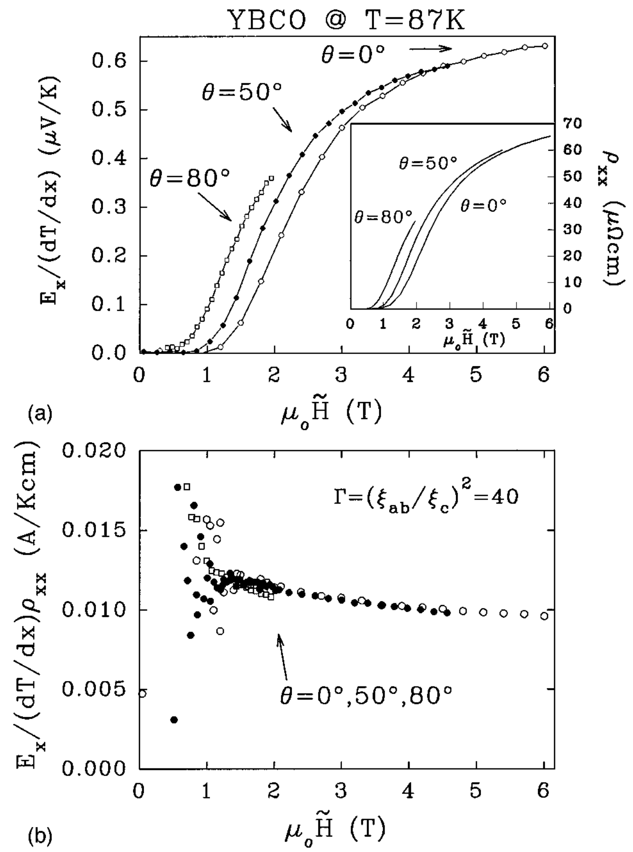

FIG. 3. (a) Seebeck signal $E_x/\nabla_x T$ vs scaled field $\tilde{H}=H\sqrt{\cos^2\theta+\Gamma^{-1}\sin^2\theta}$ for our first YBCO film at $T=87$ K ($T_c=91$ K), $\nabla_x T\cong 2$ K/cm, and $\Gamma=40$. (Inset) Longitudinal resistivity ρ_{xx} vs $\tilde{H}$. (b) The ratio of the Seebeck effect to the longitudinal resistivity $E_x/(\nabla_x T\rho_{xx})$ vs $\tilde{H}$.

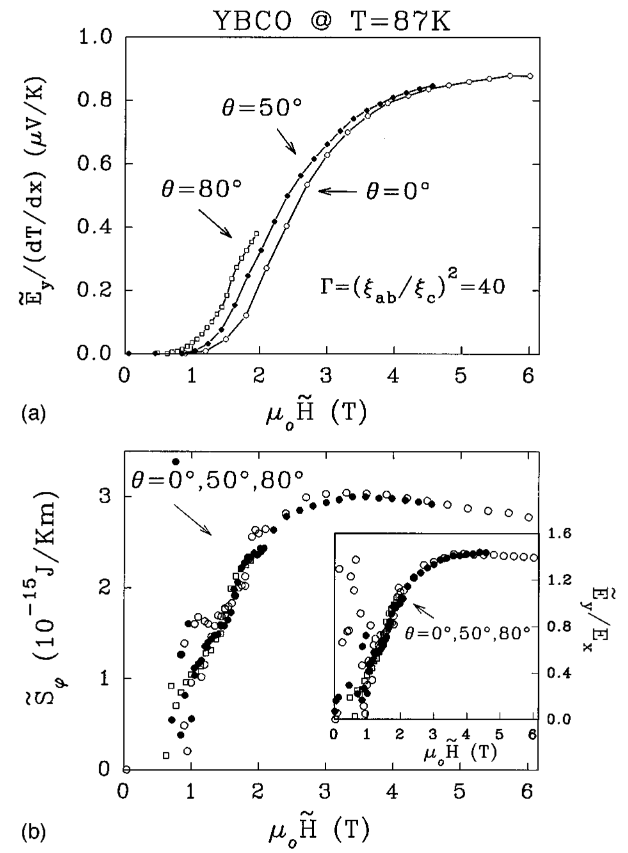

FIG. 4. (a) Scaled Nernst signal $\tilde{E}_y/\nabla_x T=(E_y/\nabla_x T)\tilde{H}/H_z=(E_y/\nabla_x T)\sqrt{1+\Gamma^{-1}\tan^2\theta}$ vs $\tilde{H}$ at $T=87$ K and $\Gamma=40$. (b) Scaled vortex transport entropy $\tilde{S}_\phi=S_\phi\tilde{H}/H_z$ vs $\tilde{H}$ for $\Gamma=40$. (Inset) The ratio of the scaled Nernst and Seebeck effects $\tilde{E}_y/E_x$ *vs* $\tilde{H}$ for $\Gamma=40$.

the transport quantities, where $\Gamma=m_c/m_{ab}=\xi_{ab}^2/\xi_c^2$ is the effective mass anisotropy ratio. In Fig. 3(a) we plot the Seebeck signal $E_x/\nabla_x T$ vs $\tilde{H}$ for θ=0°, 50°, and 80° at $T=87$ K, $\nabla_x T\cong 2$ K/cm, and $\Gamma=40$ for our first YBCO film ($T_c=91$ K). From Fig. 3(a) we see that the Seebeck effect increases as the field is tilted away from the c axis, i.e., at a given value of the anisotropically scaled field the signal increases with angle θ. We suggest this enhancement is due to the weakening of pinning by defects and the fact that the Seebeck effect is inversely related to the pinning strength γ. The enhancement vanishes as $H\rightarrow H_{c2}$, presumably due to less flux pinning at high fields. The inset shows ρ_{xx} vs $\tilde{H}$ measured in the Ohmic regime, where we see a field and angular dependence similar to that of the Seebeck effect.

In Fig. 3(b) we show the ratio of the Seebeck effect to the resistivity $(E_x/\nabla_x T)/\rho_{xx}$ vs $\tilde{H}$. As can be seen from Fig. 3(b) the data for all θ collapse to a single curve using one adjustable parameter $\Gamma=40$, in agreement with our determination of Γ from the Hall effect.[8] In view of the behavior of the Seebeck effect and resistivity in Fig. 3(a), the scaling of their ratio $(E_x/\nabla_x T)/\rho_{xx}$ $(=Q_n/\rho_n)$ is remarkable, and indicates that this quantity does not depend on flux pinning.

In Fig. 4(a) we have the scaled Nernst effect $\tilde{E}_y/\nabla_x T=(E_y\nabla_x T)\tilde{H}/H_z$ vs $\tilde{H}$ for θ=0°, 50°, and 80° and $\Gamma=40$. We note how similar the angular dependence is to that of the Seebeck effect and resistivity in Fig. 3(a). In Fig. 4(b) we now plot the scaled transport entropy $\tilde{S}_\phi=\phi_0\tilde{E}_y/(\nabla_x T\rho_{xx})$ vs $\tilde{H}$ where we observe its striking angular *independence*, again with $\Gamma=40$. The inset is a graph of the ratio of the scaled Nernst and Seebeck signals $\tilde{E}_y/E_x$ vs $\tilde{H}$ that reveals the same collapse of purely thermal data for all θ to a single curve for $\Gamma=40$. Also, the field dependence is very much like that of S_ϕ, consistent with the weak field dependence of Q_n/ρ_n in Fig. 3(b) and the fact that $E_y/E_x\propto S_\phi(\rho_n/Q_n)$. We note at low fields the transport entropy decreases with decreasing field, a result we observed over the range of our experiment, $T=89-83$ K. This is in contrast to theory where S_ϕ is expected to increase with decreasing field, and only level off in the isolated vortex limit, where the number of quasiparticle states in the core, and thus S_ϕ, become field independent.[17,18] Other measurements of S_ϕ in YBCO consist of temperature sweeps at fixed field with limited data at low fields for comparison.[19] We have carried out similar measurements on other YBCO films where we observe this downturn of S_ϕ at low fields, though the downturn is less severe in some of our samples. We believe a less pronounced downturn in S_ϕ at low fields is intrinsic to YBCO, and that sample inhomogeneities can easily affect the precise field dependence, as we have also observed in our Hall-effect measurements.[8,9] More work both experimentally and theoretically is needed to resolve these issues.

In summary, we have shown that the angular dependence of the vortex transport entropy S_ϕ, the ratio of the Nernst and Seebeck effects, and the ratio of the Seebeck effect and resistivity can be scaled in terms of the anisotropy of YBCO, where we determine $\Gamma = 40$. The angular scaling is possible because the effects of pinning drop out of these quantities, similar to the pinning independence of the Hall conductivity.[6–9] The implications of the pinning independence are important, as these quantities are not obscured by the effects of extrinsic pinning, making comparison to theory more tractable.

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