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Decomposition of the Hall angle in the mixed state of superconductors

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Abstract

Much work has gone into the study of the mixed-state Hall effect in high-temperature superconductors (HTS). One of the intriguing features is the reversal of the sign of the Hall angle upon entry into the superconducting state. A common observation for some of the HTS materials, is an empirical decomposition of the measured Hall angle into two terms, one proportional to field (like a normal metal) and the other weakly dependent on field. This observed decomposition can be explained in terms of the Hall effect within the normal vortex cores, combined with the hydrodynamic Magnus force on the body of the vortex. The problem has been treated in the framework of the time-dependent Ginzburg–Landau (TDGL) theory by Kopnin, Ivlev, and Kalatsky [J. Low Temp. Phys. 90 (1993) 1]. We show that the TDGL approach qualitatively explains the observed decomposition, and upon comparing with our data and several other published data, we find rough quantitative agreement as well. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

The mixed-state Hall effect has been a topic of much interest and one surrounded by controversy. Part of the controversy is the observed reversal in the sign of the Hall angle [1] when the temperature is reduced below T_c [1–8]. For example Fig. 1 shows our data measured on $Y_1Ba_2Cu_3O_{7-\delta}$ films [9]. At low fields α goes from a positive sign above T_c to negative below T_c.

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[1] The tangent of the Hall angle is defined as tan $\alpha = \rho_{xy}/\rho_{xx}$ where ρ_{xx} and ρ_{xy} are the longitudinal and transverse (Hall) resistivities respectively. Since the Hall angle is typically small near T_c, we will not always distinguish between the angle and its tangent in the remainder of this paper.

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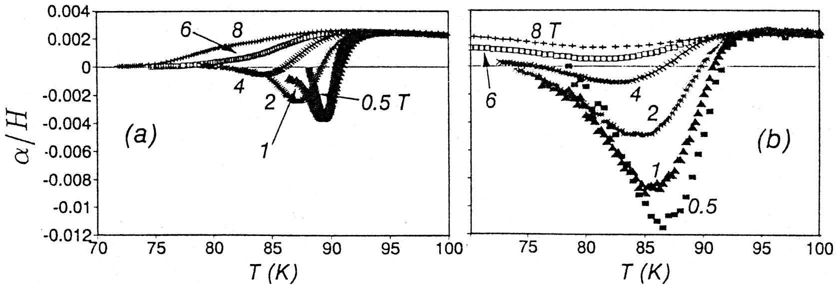

Fig. 1. (a) Temperature dependence of α/H in a YBCO film for indicated fixed fields. A continuous current density of $J = 5$ kA/cm^2 was used for these curves. (b) Similar data measured with pulsed current densities of $J = 0.7$ MA/cm^2 (for $H = 0.5$, 1, 2, and 4 T), $J = 1.1$ MA/cm^2 ($H = 6$ T) and $J = 1.5$ MA/cm^2 ($H = 8$ T). The sign reversal is significantly enhanced at higher current densities, ruling out pinning as the cause of the sign reversal.

One of the early questions that plagued the interpretation of the Hall effect is whether the sign reversal is caused by pinning [10,11]. This now seems to be resolved and it appears that the sign reversal is indeed intrinsic as it has been observed in a variety of materials and does not correlate with pinning. In fact when the influence of pinning is reduced, either by artificially controlling the defect density [12] or by overcoming pinning by a high current density [9], the sign reversal is actually enhanced. Fig. 1a and b are two sets of measurements on the same sample at low J ($= 5$ kA/cm^2) and high J ($\sim$ 1 MA/cm^2), respectively. As can be seen, the negative region of α, below T_c, is actually enhanced for the higher current (and hence lower-pinning) data.

2. Discussion

In data where pinning is not a significant factor (either because pinning is suppressed by a high current density as discussed above or because the material is intrinsicly low pinning) there is a second interesting feature that is commonly found. The Hall angle α appears to consist of two parts: (1) one part, which we call α_n, is proportional to the applied field H and has a magnitude and temperature dependence similar to that of the normal state (i.e., $\alpha_n(T) \sim H/T^2$); (2) the other term, which we call α_M, has a much smaller field dependence and a roughly common temperature dependence. This is apparent in Fig. 2 (data on $Y_1Ba_2Cu_3O_{7-\delta}$ films from Ref. [9]). The α_M shown in this figure was estimated by subtracting from the total (measured) Hall angle, the normal-core component $\alpha_n(T)$ found by fitting to its $\sim H/T^2$ behavior above T_c and extrapolating this to temperatures below T_c. The curves for 6 T and 8 T show a strong overlap, and the one at 4 T is not too far off. Furthermore, somewhat below T_c, there seems to be a tendency to saturate to a roughly common value of about 0.017. This behavior has been reported by other groups as well and the 'saturation α_M' values observed in various materials are 0.005–0.007 for $Tl_2Ba_2CaCu_2O_8$ [7,13] and 0.009–0.017 for YBCO [9,14]. Thus the values for all materials lie in the range $\sim$ 0.005–0.02. This quantitative information will serve to distinguish our mechanism

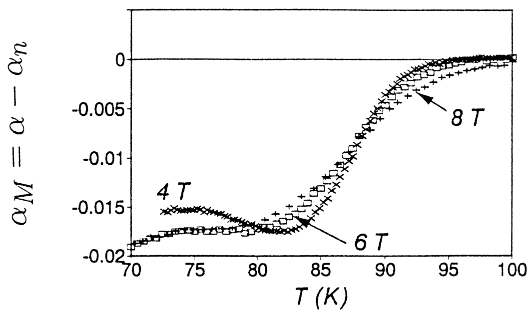

Fig. 2. Magnus-force component of the high-field Hall angle $\alpha_M = \alpha - \alpha_n$, for the data of Fig. 1. Here, $\alpha_n = 21.9 \times H/T^2$ is the observed T- and H-dependent normal-state contribution. The α_M curves show a roughly common behavior for the three fields, tending to a value of about 0.017. Our calculation yields a value of 0.014.

from an alternative mechanism (based on vortex-core charging) discussed by Khomskii and Freimuth [15], which predicts a similar decomposition of α.

The decomposition of the Hall angle into field-proportional and field-independent components can be understood as arising from the Hall effect of the normal carriers in the vortex cores and from the hydrodynamic (Magnus) force on the 'body' of the vortex respectively. The latter has been treated through the time-dependent-Ginzburg–Landau (TDGL) theory of the dynamics of the superconducting order parameter [16]. We show here that not only does the decomposition $\tan\alpha \approx \tan\alpha_n + \tan\alpha_M$ follow from the TDGL, but the magnitude of α_M obtained in this way (0.018) is in rough accord with the experimental observations ($\sim$ 0.005–0.02).

The vortex viscosity η, that governs the longitudinal conductivity consists of two parts: the Bardeen–Stephen component, which arises from dissipation of normal carriers inside the vortex core, and the Tinkham component, which arises from the dynamics of the order parameter. From Ref. [16], the net longitudinal conductivity in free flux flow is

$$\sigma \approx \sigma_n \left(\frac{\alpha u}{2} \right) \left(\frac{H_{c2}}{B} \right), \tag{1}$$

where σ_n is the normal-state conductivity, and the transverse conductivity is

$$\sigma^H \approx C \sigma_n^H \left(\frac{\alpha u}{2} \right) \left(\frac{H_{c2}}{B} \right) + \mathrm{sgn}(e)\, \sigma_n \left(\frac{\zeta \beta u}{2} \right) \left(\frac{H_{c2}}{B} \right), \tag{2}$$

where C is a constant of order unity. The first term arises from the Hall effect of normal carriers in the core, and the second term is the contribution from order-parameter dynamics. There is no contribution from quasiparticles embedded in the superfluid outside the core at zero frequency. $\alpha \sim 0.5$, $\beta \sim 0.27$, and $\zeta \approx kT_c/E_F \sim 0.03$ are constants of the TDGL theory [16]. The parameter u is the square of the ratio of the coherence length and electric-field-penetration depth. The parameters α and β are obtained from the solutions of equations describing electron-hole imbalance in a superconductor. For E_F we take the average of the values in Refs. [17–19]. The constant α should be distinguished from the Hall angle α.

From Eqs. (1) and (2) one then gets

$$\tan\alpha = \frac{\sigma^H}{\sigma} = C \frac{\sigma_n^H}{\sigma_n} + \mathrm{sgn}(e) \frac{\zeta\beta}{\alpha} \sim \alpha_n + 0.018. \tag{3}$$

This expression shows a Hall angle that decomposes into a field-proportional 'normal-core' component α_n and a field-independent term $\alpha_M \sim 0.018$, which is consistent with our experimental value of 0.017 in $Y_1Ba_2Cu_3O_{7-\delta}$, and within the general range of other experimental observations ($\sim$ 0.005–0.02). We would like to point out that Khomskii and Freimuth [15] have presented an interesting mechanism based on charging of the vortex core that explains the sign-reversing component of the mixed-state Hall effect and also predicts the qualitative decomposition $\tan\alpha_n + \tan\alpha_M$. However, their predicted estimate of α_M (which they call α_q) is about 10^{-4}, which is lower than the experimental results by about a factor of 100.

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