

The Infrared Hall Effect in YBCO: Temperature and Frequency Dependence of Hall Scattering

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We measure the Hall angle, θ_H , in YBCO films in the far- and mid-infrared to determine the temperature and frequency dependence of the Hall scattering. Using novel modulation techniques we measure both the Faraday rotation and ellipticity induced by these films in high magnetic fields to deduce the complex conductivity tensor. We observe a strong temperature dependence of the mid-infrared Hall conductivity in sharp contrast to the weak dependence of the longitudinal conductivity. By fitting the frequency dependent normal state Hall angle to a Lorentzian $\theta_H(\omega) = \omega_H/(\gamma_H - i\omega)$ we find the Hall frequency, ω_H , is nearly independent of temperature. The Hall scattering rate, γ_H , is consistent with $\gamma_H \approx T^2$ up to 200 K and is remarkably independent of IR frequency suggesting non-Fermi liquid behavior.

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DC transport measurements of high temperature superconductors in the normal state suggest different temperature dependences for the relaxation rates of longitudinal currents, $\sigma_{xx}^{-1} \sim T$, and Hall currents, $\Theta_H^{-1} \sim T^2$, where Θ_H is the Hall angle.¹ This so-called *anomalous Hall effect* is in striking contrast to the behavior of simple metals and has provoked numerous theoretical speculations.² By extending Hall measurements to the frequency domain it becomes possible to measure these relaxation rates directly and

M. Grayson, et al.

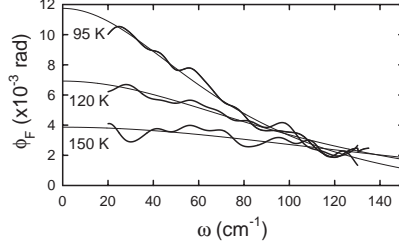


Fig. 1. The Faraday rotation, ϕ_F , as a function of frequency at several temperatures above T_C . The fits shown correspond to a Lorentzian θ_H with two fit parameters, ω_H and γ_H plotted in Fig. 3.

to examine their frequency dependence.

We have studied the magneto-optical response of optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_7$ thin films in a broad range of infrared (IR) light using two novel polarization modulation techniques³ (far-IR = 20 – 120 cm^{-1} ; mid-IR = 949 – 1079 cm^{-1}). From these measurements and the zero field optical conductivity we extract the full magneto-conductivity tensor as well as θ_H .

In the far-IR we measure the Faraday rotation, ϕ_F , by modulating linearly polarized light with a second linear polarizer that rotates at 38 Hz. The additional rotation of this light when passed through the sample at high magnetic fields, will cause a phase shift in the detector signal relative to the rotator phase. This phase shift corresponds directly to the Faraday rotation. Using a step-scan Fourier transform spectrometer as our light source we can measure the complete rotation spectrum from 20-120 cm^{-1} .

We fit the data in Fig. 1 to the empirically observed Lorentzian behavior of the Hall angle,² which follows naturally from a multiplicative two- τ model described elsewhere.¹ The Hall frequency, ω_H , and the Hall scattering rate, $\gamma_H \equiv 1/\tau_H$ are determined from the fit:

$$\theta_H \equiv \frac{\sigma_{xy}}{\sigma_{xx}} = \frac{\omega_H}{\gamma_H - i\omega} \quad (1)$$

And the experimentally measured Faraday angle, ϕ_F , is related to the Hall angle, θ_H as below (t is the electric field transmission amplitude):

$$\phi_F \equiv \frac{t_{xy}}{t_{xx}} = \frac{\theta_H}{\frac{1+n}{Z_o\sigma_{xx}} + 1} \sim \theta_H \quad (2)$$

The final approximation is valid in the limit of large σ_{xx} as in our case. (n is the index of refraction of the substrate and Z_o the impedance of free space.) The results of the fits are shown in Fig. 1, with the extracted

The Infrared Hall effect in YBCO

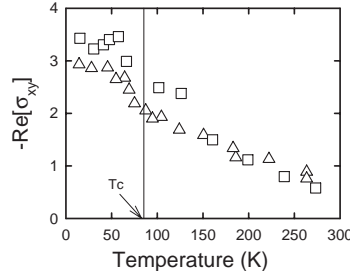


Fig. 2. The Hall conductivity (real part) as a function of temperature at 8 T. ($\Delta = 949 \text{ cm}^{-1}$, and $\square = 1079 \text{ cm}^{-1}$).

Lorentzian fit parameters γ_H and ω_H plotted in Fig. 3. The Hall scattering rate, γ_H fits a T^2 dependence (solid line, Fig. (3b)). This result justifies an assumption of previous DC transport analysis,¹ namely that the scattering rate, γ_H , carries all the temperature dependence of the Hall angle and ω_H stays constant. We remark that the Hall relaxation rate at 100 K is smaller than the σ_{xx} relaxation rate by a factor of 3.

In the mid-IR we use a CO₂ laser as a light source tunable from 949 cm^{-1} to 1079 cm^{-1} and analyze the light transmitted through the sample with a photoelastic modulator oscillating at 50 kHz. This measurement allows simultaneous measurement of both the Faraday rotation and ellipticity induced by the sample by looking at different harmonics of the modulation frequency. These quantities can then give us both the real and imaginary parts of the Hall angle, θ_H .³

The mid-IR Hall conductivity extracted from these measurements is shown in Fig. 2. The temperature dependence is clearly very strong, in contrast to the well documented weak temperature dependence of the longitudinal conductivity at the same frequency (less than 20 % change over the same temperature range.)^{4,5} This contrast suggests different scattering mechanisms are responsible for relaxing longitudinal and Hall currents.

At high frequencies the use of Eq. 1 is justified since it describes the asymptotic behavior of the Hall angle in the high frequency limit. ω_H and γ_H extracted from these fits are shown in Fig. 3. The mid- and far-IR results for γ_H are practically identical telling us that the dependence of the Hall relaxation on frequency is very weak. However the predicted behavior of a Fermi liquid with the observed far-IR T^2 behavior is:

$$\gamma_H \propto [\omega^2 + (\pi T)^2] \quad (3)$$

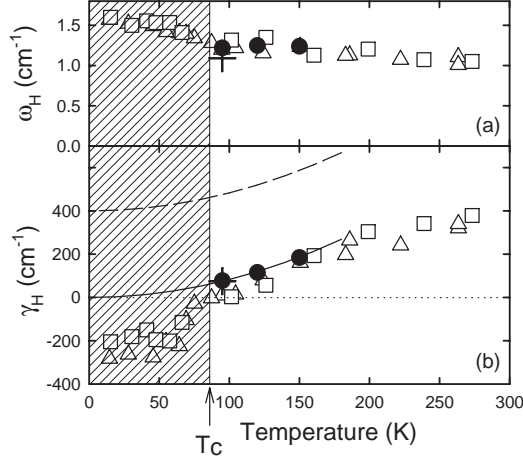


Fig. 3. (a) The Hall frequency, ω_H , and (b) the Hall scattering rate, γ_H , as a function of temperature at 8 T for far-IR ($\bullet = 20\text{-}120\text{ cm}^{-1}$) and mid-IR ($\Delta = 949\text{ cm}^{-1}$, and $\square = 1079\text{ cm}^{-1}$) frequencies. The solid line in (b) shows a T^2 fit to the far-IR data, with the dashed line showing the expected mid-IR Hall scattering rate based on Fermi liquid theory (Eq. (2)). (Eq. 1 ceases to be relevant below T_c , but the data are plotted for completeness.)

The resulting expected γ_H for a Fermi liquid at $\omega = 1000\text{ cm}^{-1}$ is shown as a dashed line in Fig. (3b) and clearly disagrees with the observed mid-IR γ_H , suggesting non-Fermi liquid behavior.

Note that these results contrast recent ARPES measurements of the quasiparticle width in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ along the (π, π) direction of the Brillouin zone.⁶ Both this experiment and measurements of longitudinal conductivity are consistent with $1/\tau \sim \max(\omega, \pi T)$. We conclude that Hall transport in high T_c materials has a fundamentally different relaxation mechanism than either the longitudinal conductivity or quasi particle lifetime.

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