J. Phys.: Condens. Matter **10** (1998) 5955–5964. Printed in the UK PII: S0953-8984(98)90307-1

Universal vortex-state Hall conductivity of $YBa_2Cu_3O_7$ single crystals with differing correlated disorder

D A Beam†, N-C Yeh† and F Holtzberg‡

† Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA
‡ IBM, Thomas J Watson Research Center, Yorktown Heights, NY 10598, USA

Received 5 January 1998

Abstract. The vortex-state Hall conductivity (σ_{xy}) of $YBa_2Cu_3O_7$ single crystals in the anomalous-sign-reversal region is found to be independent of the density and orientation of the correlated disorder. After the anisotropic-to-isotropic scaling transformation is carried out, a universal scaled Hall conductivity $\tilde{\sigma}_{xy}$ is obtained as a function of the reduced temperature (T/T_c) and scaled magnetic field strength ($\tilde{H}$) for five samples with different densities and orientation of controlled defects. The transport scattering times (τ), derived from applying the model given by Feigel'man *et al* (Feigel'man M V, Geshkenbein V B, Larkin A I and Vinokur V M 1995 *Pis. Zh. Eksp. Teor. Fiz.* **62** 811 (Engl. Transl. 1995 *JETP Lett.* **62** 835)) to the universal Hall conductivity $\tilde{\sigma}(T/T_c, \tilde{H})$, are consistent in magnitude with those derived from other measurements for quasiparticle scattering, and are much smaller than the thermal relaxation time of vortex displacement and than the vortex–defect interaction time. Our experimental results and analyses therefore suggest that the anomalous sign reversal in the vortex-state Hall conductivity is associated with the intrinsic properties of type-II superconductors, rather than extrinsic disorder effects.

1. Introduction

There has been progress in achieving an understanding of the observed anomalous sign reversal of the vortex-state Hall conductivity (σ_{xy}) of various type-II superconductors [1–10]. It has been suggested that the sign reversal is an intrinsic property of type-II superconductors in the vortex state whenever the transport mean free path ℓ becomes comparable to that of the vortex core size ξ [2]. However, the problem of the physical origin of the sign reversal is not resolved, and areas of controversy remain. One area of controversy is that of the effects of pinning and defects on the vortex-state Hall conductivity [3–5]. Vinokur *et al* [3] argued that randomly distributed pinning sites do not contribute to σ_{xy}. Samoilov *et al* [4] found little change in the σ_{xy} before and after c-axis-oriented columnar defects were introduced in a $YBa_2Cu_3O_7$ single crystal and in a $Tl_2Ba_2CaCu_2O_8$ film, when measured with the applied magnetic field oriented along each sample's c-axis. In contrast, Kang *et al* [5] reported defect dependence in σ_{xy} at low temperatures after comparing, under the same conditions as for Samoilov *et al* [4], σ_{xy} of an as-grown $YBa_2Cu_3O_7$ single crystal with that of one with c-axis columnar defects. Kang *et al* [5] therefore suggested the addition of a pinning-dependent term to the theory given by Vinokur *et al* [3] to represent the observed low-temperature defect dependence. However, the defect dependence observed by Kang *et al* was questioned, in view of the fact that $\sigma_{xy} \equiv \rho_{xy}/(\rho_{xx}^2 + \rho_{xy}^2)$, large errors may exist in the low-temperature σ_{xy}-data due to the rapidly vanishing longitudinal resistivity

ρ_{xx} and Hall resistivity ρ_{xy} [11]. Even so, the assumption made by Vinokur *et al* [3] of completely random pinning sites is not necessarily applicable to systems with correlated disorder [12] such as those containing columnar defects. Additionally, Vinokur *et al* [3] implicitly assumed a defect-independent scattering time (τ) and a defect-independent vortex phase transition temperature. A more general model for the vortex-state Hall conductivity has been proposed by Feigel'man, Geshkenbein, Larkin and Vinokur (FGLV) [1]. This model attributes the sign reversal in the vortex state σ_{xy} to the difference in carrier densities $\delta n \equiv n_0 - n_\infty$, where n_0 is the carrier density on the axis of the vortex core, and n_∞ is the carrier density far outside of the vortex core. The carrier scattering mechanism is not specified and is represented by a transport scattering time τ.

We report in this paper the observation of defect-independent vortex-state Hall conductivity in five $YBa_2Cu_3O_7$ single crystals with different densities and orientations of columnar defects. Using the anisotropic-to-isotropic scaling transformation [7, 13] to remove the effects due to the electronic mass anisotropy, we obtain a universal, scaled Hall conductivity $\tilde{\sigma}_{xy}$ as a function of the reduced temperature (T/T_c) and the scaled magnetic field strength ($\tilde{H}$). We infer, from the defect independence, that the quasiparticle scattering process in the vortex-state Hall conductivity does not directly involve static disorder. We also report on the consistency of the magnitudes of τ derived from our data using the FGLV model [1] with the quasiparticle lifetimes determined from various other measurements [6, 14, 15]. The universal vortex-state Hall conductivity and the consistency of the characteristic time τ of the Hall conduction with that of the quasiparticles suggest that the anomalous sign reversal in the vortex-state Hall conductivity is the result of intrinsic properties of type-II superconductors.

Table 1. A summary of the superconducting transition temperatures T_c, normal-state resistivities $\rho_{xx}(T_c)$, and sample thicknesses for the five $YBa_2Cu_3O_7$ single crystals used in this work.

Sample	T_c (K)	$\rho_{xx}(T_c)$ (10^{-8} Ω m)	Thickness (μm)
As-grown	92.9	32.4	42.7
(c, 2 T)	92.7	33.2	37.7
(45°, 2 T)	92.9	35.6	21.0
(c, 0.5 T)	92.6	34.0	26.3
(45°, 0.5 T)	92.8	34.4	18.9

2. Experimental procedure

Our experimental investigations were conducted using five $YBa_2Cu_3O_7$ single crystals, one heavily twinned as-grown sample (with an average twin separation $\sim$1 μm), and four samples with comparably dilute twin densities (with an average twin separation $\sim$10 μm), which were irradiated with 5 GeV Pb ions [16] to create different conditions of columnar defects. Before irradiation, the superconducting transition temperatures of the samples were about 93.0 K, with resistive transition widths $\sim$0.2 K. The approximate sample area was 0.5 mm $\times$ 0.5 mm and the thickness of each sample is tabulated in table 1. Gold contacts of $\sim$100 nm thickness were sputtered onto the four corners of the samples. The fluences of the Pb ions were 10^{15} m^{-2} (which corresponds to a matching field $B_\phi = 2$ T [16], equivalent to an average column separation $d_r \approx 35$ nm) on two samples, and 2.5×10^{14} m^{-2} (corresponding to $B_\phi = 0.5$ T and an average column separation $d_r \approx 70$ nm) on the other two. The columnar defects were oriented along the crystalline c-axis for two samples

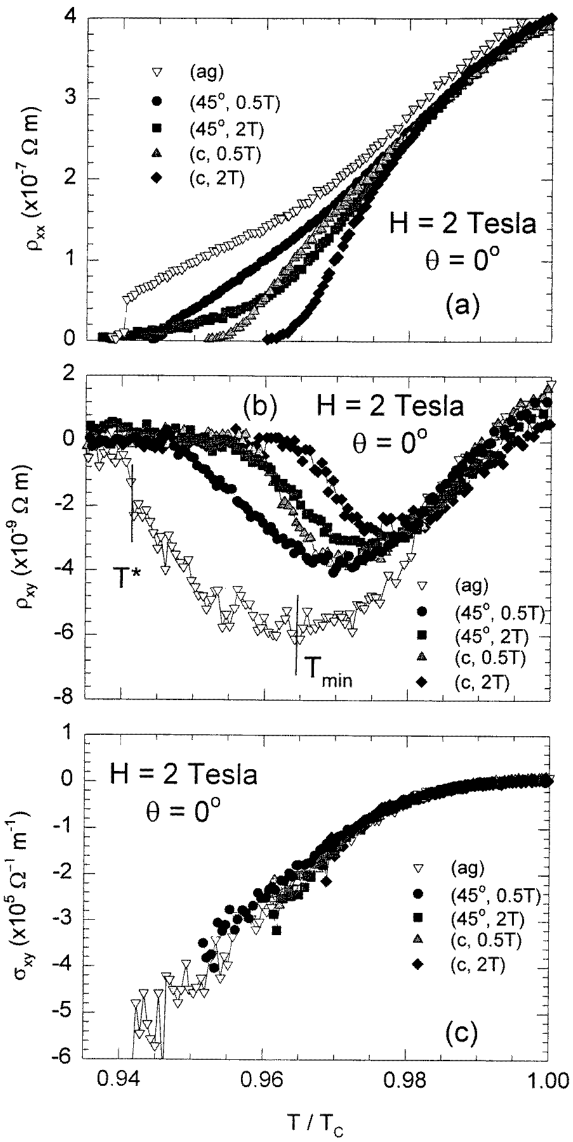

Figure 1. Representative data for five $YBa_2Cu_3O_7$ single crystals at $H = 2$ T and for $\boldsymbol{H} \parallel \hat{c}$: (a) ρ_{xx} versus T/T_c; (b) ρ_{xy} versus T/T_c; and (c) σ_{xy} versus T/T_c. We note that the Hall conductivity $\sigma_{xy}(T/T_c)$ for a given magnetic field strength and orientation is defect independent.

with $B_\phi = 0.5$ T ($c, 0.5$ T), and $B_\phi = 2$ T ($c, 2$ T), and along the 45° direction relative to the c-axis for the other two samples, with $B_\phi = 0.5$ T ($45^\circ, 0.5$ T), and $B_\phi = 2$ T ($45^\circ, 2$ T). We note that the densities of columnar defects in all of the irradiated samples are more than four orders of magnitude larger than those of the twin boundaries. Hence, it is reasonable to assume in the following that the pinning contribution from twin boundaries is negligible relative to that of columnar defects in the irradiated samples. The irradiated samples demonstrated slight suppression (between 0.05 and 0.2 K) of the zero-field transition temperature T_c, with minimal changes to the transition width and the normal-state resistivity.

The T_c-values are 92.6 K for $(c, 0.5\text{ T})$, 92.7 K for $(c, 2\text{ T})$, 92.8 K for $(45^\circ, 0.5\text{ T})$, 92.9 K for $(45^\circ, 2\text{ T})$, and 92.9 K for the as-grown crystal. Measurements of both ρ_{xx} and ρ_{xy} were made on all samples to yield the Hall conductivity σ_{xy}. The data were analysed using the van der Pauw corrections [17] for all measurement configurations, involving electrical contacts at the four corners. The zero-field normal-state resistivity $\rho_{xx}(T_c)$ and the sample thicknesses are summarized in table 1.

The temperature-dependent measurements were made at five different constant applied magnetic fields, $H = 1$, 2, 3, 4, and 6 T, with the angle θ of the magnetic field relative to the sample c-axis set at 0°–6°, 9°, 14°, 30°, 40°–50°, and 60° (some angles not for all samples). The magnetic-field-dependent measurements were made from 0 to 6 T at three constant temperatures, $T = 88.0$, 90.0, and 92.0 K, and again at various angles θ. All of the measurements were made in the linear response regime with current densities $<3.5 \times 10^4$ A m^{-2}, established from the current–voltage characteristics, to ensure that both ρ_{xx} and ρ_{xy} were independent of the applied current.

3. Results and the scaling transformation

Representative sets of ρ_{xx}, ρ_{xy}, and σ_{xy} versus T/T_c data for the five $YBa_2Cu_3O_7$ single crystals are plotted in figures 1(a)–1(c) respectively, for $H = 2.0$ T and $\boldsymbol{H} \parallel \hat{\boldsymbol{c}}$. To avoid large errors in the low-temperature σ_{xy}-data due to the rapidly vanishing ρ_{xx} and ρ_{xy}, we restrict our analyses of the vortex-state σ_{xy}-data to temperatures above a lowest temperature T^*, where $T^* < T_{min}$ and $\rho_{xy}(T^*) = 0.25\rho_{xy}(T_{min})$, where T_{min} is the temperature at which ρ_{xy} is a minimum, as illustrated in figure 1(b). Also, as van der Pauw corrections are only valid in the linear response limit [17], restricting analyses to data above this lowest temperature ensures that analyses are performed in the ohmic regime for both ρ_{xx} and ρ_{xy}. As is evident from the σ_{xy} versus T/T_c data with $H = 2$ T and $\boldsymbol{H} \parallel \hat{\boldsymbol{c}}$ for the five $YBa_2Cu_3O_7$ single crystals shown in figure 1(c), the vortex-state Hall conductivity, $\sigma_{xy}(T/T_c)$, is universal for all samples for a given applied field strength (H).

The vortex-state σ_{xy} versus T/T_c data, with $H = 2$ T and $\boldsymbol{H}$ oriented at various angles (θ) relative to the sample c-axis, are plotted in figure 2(a) for the $(c, 0.5\text{ T})$ sample. We find that the angular dependence of σ_{xy} is entirely determined by the mass anisotropy [13]. That is, the scaled Hall conductivity, $\tilde{\sigma}_{xy} \equiv \sigma_{xy}\sqrt{1 + \varepsilon^2 \tan^2\theta}$, is uniquely determined by the reduced temperature (T/T_c) and the scaled field $\tilde{H} = H\sqrt{\cos^2\theta + \varepsilon^2 \sin^2\theta}$, according to the anisotropic-to-isotropic scaling transformation relations of the anisotropic Ginzburg–Landau theory [13]. Here $\varepsilon^{-2} \equiv (m_c/m_{ab}) \approx 60$ [13, 18] is the effective-mass ratio for $YBa_2Cu_3O_7$. The scaled $\tilde{\sigma}_{xy}$ versus T/T_c data for a scaled field of $\tilde{H} = 2$ T at $\theta = 0^\circ, 45^\circ$, and 60° are plotted in the inset of figure 2(a) for $(c, 0.5\text{ T})$. Similarly, σ_{xy} versus H data at $T/T_c \approx 0.97$ are shown in figure 2(b) for the as-grown $YBa_2Cu_3O_7$ single crystal, and the scaled $\tilde{\sigma}_{xy}$ versus $\tilde{H}$ data for $T/T_c \approx 0.97$ are illustrated in the inset.

The angular dependence of the vortex-state σ_{xy} is also universal for the five $YBa_2Cu_3O_7$ single crystals, as is evident from the data plotted in figure 3, including its inset. The scaled $\tilde{\sigma}_{xy}$ versus T/T_c curves for the four $YBa_2Cu_3O_7$ single crystals with columnar defects, and under $\tilde{H} = 2$ T and $\tilde{H} = 1$ T, are shown in figure 3. The leftmost curve corresponds to the scaled data for four samples at $(H, \theta) = (4\text{ T}, 60^\circ)$ and $(2\text{ T}, 0)$, which are equivalent to those for $\tilde{H} = 2$ T. The rightmost curve corresponds to those at $(H, \theta) = (2\text{ T}, 60^\circ)$ and $(1\text{ T}, 0)$, equivalent to those for $\tilde{H} = 1$ T. The defect independence of the Hall conductivity is further demonstrated by the σ_{xy} versus T/T_c data with $H = 2$ T and $\theta = 45^\circ$ in the inset of figure 3 for all five $YBa_2Cu_3O_7$ single crystals. Hence, given the results shown in figure 1(c),

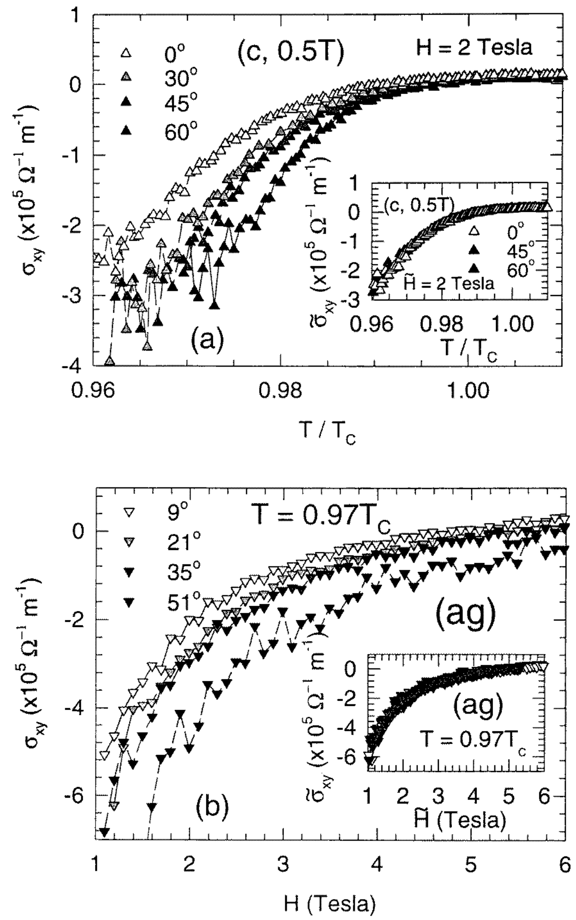

Figure 2. (a) Representative angle-dependent σ_{xy} versus T/T_c data for one $YBa_2Cu_3O_7$ single crystal (c, 0.5 T) measured with $H = 2$ T and for θ varying from 0 to 60°. Inset: scaled $\tilde{\sigma}_{xy}$ versus T/T_c data for the scaled field $\tilde{H} \equiv H\sqrt{\cos^2\theta + \varepsilon^2 \sin^2\theta} = 2$ T for (c, 0.5 T). (b) Angle-dependent σ_{xy} versus H data for the as-grown $YBa_2Cu_3O_7$ single crystal at $T = 0.97T_c$. Inset: scaled and universal $\tilde{\sigma}_{xy}$ versus $\tilde{H}$ data at $T = 0.97T_c$ for three $YBa_2Cu_3O_7$ single crystals, as-grown, (c, 2 T), and (45°, 2 T). These data indicate that $\tilde{\sigma}_{xy}$ is uniquely determined by T/T_c and $\tilde{H}$, and is disorder independent.

the insets of figures 2(a) and 2(b), as well as figure 3 and its inset, we can conclude that the scaled Hall conductivity $\tilde{\sigma}_{xy}$ of YBCO is uniquely determined by the variables T/T_c and $\tilde{H}$, and is completely independent of correlated disorder in the ohmic regime of the vortex state. These results suggest that the assertion of defect-independent vortex-state Hall conductivity, originally made by Vinokur *et al* [3] for random point defects, appears to hold even for correlated disorder, at least in the flux-flow regime of the vortex state. This universal behaviour in the scaled Hall conductivity $\tilde{\sigma}_{xy}$ is in sharp contrast to the significant reduction in the mixed-state longitudinal resistivity, ρ_{xx}, and in the magnitude of the sign-reversed Hall resistivity, ρ_{xy}, due to the presence of columnar defects [19]. (See figures 1(a)–1(c) for representative data for $\theta = 0°$, where $\sigma_{xy}(T/T_c, H, \theta = 0°) = \tilde{\sigma}_{xy}(T/T_c, \tilde{H})$, according to reference [13].)

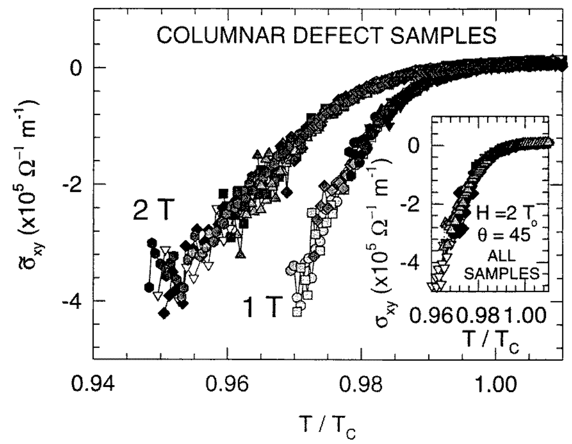

Figure 3. Defect-independent $\tilde{\sigma}_{xy}$ versus T/T_c data for four $YBa_2Cu_3O_7$ single crystals with columnar defects for two different scaled fields: $\tilde{H} = 1$ T and $\tilde{H} = 2$ T. The leftmost curve corresponds to the scaled data for four samples at $(H, \theta) = (4\ \mathrm{T}, 60^\circ)$ and $(2\ \mathrm{T}, 0^\circ)$, equivalent to $\tilde{H} = 2$ T, and the rightmost curve corresponds to those at $(H, \theta) = (2\ \mathrm{T}, 60^\circ)$ and $(1\ \mathrm{T}, 0^\circ)$, equivalent to $\tilde{H} = 1$ T. Inset: σ_{xy} versus T/T_c data for five $YBa_2Cu_3O_7$ single crystals at $H = 2$ T and $\theta = 45^\circ$, showing universal σ_{xy} versus T/T_c data for all samples with $\tilde{H} = \sqrt{2}$ T.

4. Analyses using the FGLV model

Next, we attempt to achieve a better understanding of the physical significance of the vortex-state Hall conductivity by analysing our data using the FGLV model [1]. The FGLV model describes σ_{xy} under a magnetic induction B (in CGS units) as follows [1]:

$$\sigma_{xy} = \frac{nec}{B}\left[g\frac{(\omega_0\tau)^2}{1+(\omega_0\tau)^2} - \frac{\delta n}{n}\right] + \sigma_{xy}^n(1-g) \qquad \sigma_{xy}^n \equiv \frac{nec}{B}\frac{(\omega_c\tau)^2}{1+(\omega_c\tau)^2} \tag{1}$$

where n is the total carrier density, δn ($\equiv n_0 - n_\infty$) satisfies the conditions $\delta n \ll n$ ($\approx n_0 \approx n_\infty$), $\delta n \to$ constant for $T \to 0$ and $\delta n \to 0$ for $T \to T_c^-$; $\omega_0 = \Delta^2/(\hbar E_F)$ is associated with the quasiparticle energy state, with Δ being the temperature-dependent superconducting energy gap and E_F the Fermi energy; σ_{xy}^n is the normal-state Hall conductivity, where $\omega_c \equiv eB/m^*c$ is the cyclotron frequency of normal carriers; and g is a function dependent on the ratio $\Delta/(k_BT) \equiv x$, which satisfies the conditions $g(x \gg 1) \to 1$ and $g(x \to 0) \approx x$ [1], so $(1-g)$ is associated with the normal carrier contribution. In the event that $\delta n > 0$ [20], sign reversal in σ_{xy} can take place as the temperature is varied [1]. We note that the FGLV model assumes an isotropic superconductor. Hence, the model should be directly compared with the scaled Hall conductivity $\tilde{\sigma}_{xy}$ in our data analyses.

To quantify the transport scattering time τ, we take $\delta n/n$, Δ, and E_F to be defect independent. Using $\delta n/n \equiv (\Delta/E_F)^2$ [1], $E_F = 1210$ K [21], and $\Delta(T) \approx \Delta_0|1-(T/T_c)|^\alpha$, where $\Delta_0 \approx 5.2k_BT_c$ is the zero-temperature superconducting energy gap empirically determined from the low-temperature scanning tunnelling spectroscopy and averaged over the k-space [22], and $\alpha = 1/2$ for the BCS-like temperature dependence and $\alpha = 2/3$ for the three-dimensional XY-model [23], we apply equation (1) to $\tilde{\sigma}_{xy}(T/T_c, \tilde{H})$ and obtain $\tau(T/T_c, \tilde{H})$. The τ-values for various scaled magnetic field strengths ($\tilde{H} = 1$ T, 2 T, and 4 T) as a function of the reduced temperature T/T_c are shown in figure 4 for the XY-model ($\alpha = 2/3$), and in the inset of figure 4 for the BCS-like function ($\alpha = 1/2$). We

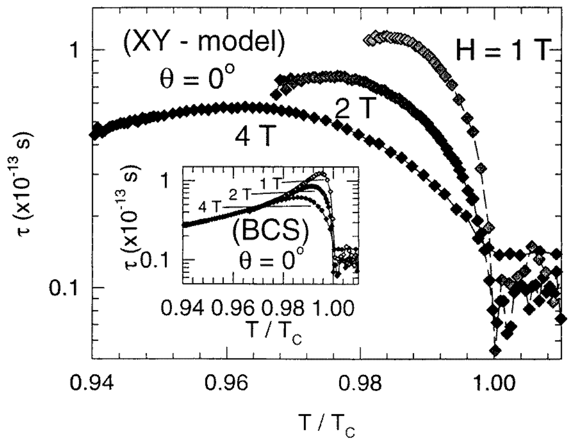

Figure 4. τ versus T/T_c data for $YBa_2Cu_3O_7$ single crystals for different scaled magnetic fields $\tilde{H} = 1$ T, 2 T, and 4 T, obtained using the XY-model for the superconducting energy gap $\Delta(T \leqslant T_c) = \Delta_0[1 - (T/T_c)]^{2/3}$ in equation (1). Here τ has been derived from the universal function $\tilde{\sigma}_{xy}(T/T_c, \tilde{H})$. Inset: the corresponding τ versus T/T_c curves obtained using the BCS energy gap $\Delta(T \leqslant T_c) = \Delta_0[1 - (T/T_c)]^{1/2}$ in equation (1).

note that τ appears comparable in magnitude for the two α-values, and τ decreases with increasing T near T_c. The magnitude of τ ranges from $\sim 10^{-13}$ s below T_c to $\sim 10^{-14}$ s above T_c, consistent with the measurements of the thermal conductivity [14], microwave surface resistance [15], and optical conductivity [6]. We caution that the detail of the temperature dependence of τ, such as the slight decrease in τ at temperatures below $0.98T_c$, should not be taken literally. The theoretical simplifications (such as the neglect of the order parameter fluctuations near T_c [24] and the anisotropic superconducting gap [22]) in the FGLV model, and the uncertainties in the empirical value of Δ_0 (with smaller Δ_0 yielding larger τ at low temperatures according to equation (1)), contribute to uncertainties in the exact temperature dependence of τ. Furthermore, the slight differences in the τ-values above T_c for various scaled magnetic fields ($\tilde{H}$) are within the experimental resolution, and therefore should not be over-interpreted.

5. Discussion—comparison of characteristic times

To gain further insight into the magnitude of the defect-independent quasiparticle scattering time τ, we consider two typically relevant characteristic times, the vortex–column interaction time t_{col}, and the vortex thermal relaxation time t_{th}, and we assume that the line tension of vortices is still finite in the vortex liquid state. We may approximate t_{col}, the time required for the inhomogeneous vortex structure to relax due to the presence of columnar defects, by the expression $t_{col} \approx r_p/v_c$, where r_p is the pinning range of a columnar defect, and v_c is the vortex critical velocity given by $v_c = j_c\Phi_0/(\eta c)$, with j_c being the critical current density, η the viscosity, and Φ_0 the flux quantum. To estimate r_p and j_c, we note that the temperature range of our experiments is significantly above the 'delocalization temperature' T_{dl} [13], where T_{dl} corresponds to the temperature above which the root mean square thermal displacement of vortices, $\sqrt{\langle u^2 \rangle_{th}}$, becomes larger than the average separation of columnar defects d_r [13]. In the case of $YBa_2Cu_3O_7$, $T_{dl} \sim 85$ K has been estimated [13]. If we define a crossover field $B_{rb}(T)$ which separates the single-vortex pinning regime at

$B < B_{rb}(T)$ from the collective pinning regime at $B > B_{rb}(T)$, the critical current density j_c for magnetic fields parallel to the columns and at $T > T_{dl}$ can be expressed as [13, 25]

$$j_c(T > T_{dl}) \approx \begin{cases} \left(\dfrac{\xi r_r^2}{2d_r^3}\right)\left[\dfrac{(\varepsilon\varepsilon_0 r_r/\pi)\ln(d_r^2/2\xi^2)}{k_B T}\right]^4 j_0 & (B < B_{rb}) \\ \left(\dfrac{\xi r_r^2}{d_r^3}\right)\left[\dfrac{B}{B_{rb}}\right]^{1/4}\left[\dfrac{(\varepsilon\varepsilon_0 r_r/\pi)}{k_B T}\right]^4 j_0 & (B > B_{rb}) \end{cases} \tag{2}$$

where the crossover field B_{rb} is given by [17, 25]

$$B_{rb}(T > T_{dl}) \approx B_\phi \left(\frac{r_r}{d_r}\right)^2 \left[\frac{(\varepsilon\varepsilon_0 r_r/\pi)\ln(d_r^2/2\xi^2)}{k_B T}\right]^6. \tag{3}$$

ε is the anisotropy parameter defined by $\varepsilon^{-2} \equiv m_c/m_{ab}$; $\varepsilon_0 \equiv [\Phi_0/(4\pi\lambda)]^2$, with λ being the magnetic penetration depth; r_r is the radius of columnar defects, k_B the Boltzmann constant, and $j_0 \equiv (4c\varepsilon_0)/(3\sqrt{3}\xi\Phi_0)$ is the depairing current density. Using equation (2) and the Bardeen–Stephen viscosity $\eta = \Phi_0 H_{c2}/(\rho_n c^2)$, with ρ_n being the normal-state resistivity at T_c and $H_{c2} = \Phi_0/(2\pi\xi^2)$ being the upper critical field, we obtain

$$\begin{aligned} t_{col} &\approx \frac{r_p}{v_c} = \frac{r_p H_{c2}}{j_c \rho_n c^2} = \frac{r_p \Phi_0/(2\pi\xi^2)}{j_c\rho_n c^2} \\ r_p &\approx [\xi^2 + \langle u^2\rangle_{th}]^{1/2} \\ \langle u^2\rangle_{th}^{1/2} &\approx d_r \left[\frac{k_B T}{(\varepsilon\varepsilon_0 r_r/\pi)\ln(d_r^2/2\xi^2)}\right]^2. \end{aligned} \tag{4}$$

Using the experimental parameters $B = B_\phi = 2$ T and $T/T_c = 0.98$, as well as the following material parameters for $YBa_2Cu_3O_7$ single crystals: $\xi(0) = 1.2$ nm, $\xi(T) = \xi(0)|1 - (T/T_c)|^{-1/2}$, $\lambda(0) = 140$ nm, $\lambda(T) = \lambda(0)|1 - (T/T_c)^4|^{-1/2}$, $T_c = 93$ K, $r_r = 3.5$ nm, $\rho_n = 6 \times 10^{-7}$ Ω m, and $\varepsilon^{-2} = 60$ [18], we obtain $B_{rb} \approx 6.7 \times 10^{-8}$ T $\ll B$, and $j_c \approx 5.4 \times 10^3$ A m^{-2} using the expression in equation (2) for $B > B_{rb}$. Thus, $t_{col} \approx 6.5 \times 10^{-4}$ s from equation (4) for $T = 0.98T_c$, and $t_{col} \gg \tau$ holds for the entire experimental temperature range, so the Hall conduction time τ appears to be unrelated to the vortex–column interaction. It is worth noting that according to equation (4), the root mean square displacement of vortices, $\sqrt{\langle u^2\rangle_{th}}$, becomes much larger than the average separation d_r between neighbouring columnar defects: for $(T/T_c) = 0.98$, we obtain $\sqrt{\langle u^2\rangle_{th}} \approx 13.1 d_r$. This large vortex displacement is consistent with the large degree of thermal wandering of vortices at $T > T_{dl}$ [13]. In other words, vortices are no longer confined by either columnar defects or the vortex–vortex interaction. Therefore each wandering vortex interacts with several columnar defects within the characteristic time t_{col}. This estimated t_{col} demonstrates the large difference between the magnitude of t_{col} and that of the Hall conduction time τ, thereby strongly suggesting the irrelevance of correlated disorder to the vortex-state Hall conductivity.

We may also compare τ with the characteristic thermal relaxation time of vortex displacement t_{th}, which is associated with the short-scale elastic deformation of vortices, and is given by [13]

$$t_{th} \approx \frac{8\kappa^2 a_0^2}{\rho_n c^2} \tag{5}$$

with $\kappa \equiv \lambda/\xi$ being the Ginzburg–Landau parameter and a_0 the Abrikosov lattice constant. Using $H = 2$ T, we find that $t_{th} \approx 2 \times 10^{-11}$ s. The fact that $t_{th} \gg \tau$ implies that the thermal relaxation of vortex displacement is not relevant to the characteristic Hall conduction time in the vortex liquid state.

The above estimates of different times suggest that the scattering mechanism in the vortex-state Hall conductivity is *not* directly related to either the thermal displacement of vortices or the vortex–column interaction, provided that the concept of vortex lines is still valid in the liquid state. Furthermore, the observation of a complete disorder-independent vortex-state Hall conductivity $\tilde{\sigma}_{xy}$, and that of a characteristic Hall conduction time τ comparable in magnitude to the quasiparticle scattering time, strongly suggest that the underlying mechanism in the sign-reversal regime of the Hall conductivity is associated with a process intrinsic to the vortex state of type-II superconductors. One possibility may be related to the thermal fluctuation effects of the superconducting order parameter, which are most significant near T_c where our data have been taken. However, in contrast to the known *disorder-dependent* fluctuation conductivity proposed by Maki and Thompson [26, 27], our observation of *defect-independent* vortex-state Hall conductivity implies that thermal fluctuations alone cannot entirely account for our data. On the other hand, since the effects of thermal fluctuations on σ_{xx} may be different from those on σ_{xy}, we cannot reach a conclusion as to whether thermal fluctuations of the order parameter may be relevant to the anomalous sign reversal in $\tilde{\sigma}_{xy}(T < T_c)$ of various type-II superconductors or not. Furthermore, recent theoretical studies [28, 29] suggest that strong vortex-loop excitations near the vortex-solid-to-liquid phase transition may render the concept of vortex line liquid invalid, at least in the clean limit. Hence, our analysis of various characteristic times, which are based on the assumption of vortex line tensions in the vortex liquid state [13], may have to be re-examined. Better understanding of the microscopic mechanism of the vortex-state Hall conduction awaits more theoretical investigation.

6. Conclusion

In summary, we have observed defect-independent vortex-state Hall conductivity of five $YBa_2Cu_3O_7$ single crystals with different types and densities of correlated disorder. The general temperature and magnetic field dependence of the scaled Hall conductivity, $\tilde{\sigma}_{xy}(T/T_c, \tilde{H})$, after removing the effects of electronic mass anisotropy via the anisotropic-to-isotropic scaling transformation, can be consistently described in terms of the FGLV theory [1], and the temperature- and magnetic-field-dependent transport scattering times (τ) for the Hall conduction are derived from the universal $\tilde{\sigma}_{xy}$, and are found to be comparable in magnitude to the quasiparticle scattering times determined from measurements of thermal conductivity, microwave surface impedance, and optical conductivity. Furthermore, τ is much smaller than the thermal relaxation time (t_{th}) of the vortex displacement and than the vortex–column interaction time (t_{col}). Our results on the defect-independent vortex-state Hall conductivity, and the relevance of quasiparticle scattering in the anomalous-sign-reversal region of $\tilde{\sigma}_{xy}$, call for further investigation of the microscopic mechanism for Hall conduction in the vortex state of type-II superconductors.

Acknowledgments

This work was supported by NSF Grant No DMR-9401315, ONR Grant No N00014-91-J-1556, and the Packard Foundation. We gratefully acknowledge Dr Marcin Konczykowski for performing the ion irradiation at GANIL in Caen, France, and for his insightful comments. We also thank Dr Arkadii V Samoilov for useful comments.

References

[1] Feigel'man M V, Geshkenbein V B, Larkin A I and Vinokur V M 1995 *Pis. Zh. Eksp. Teor. Fiz.* **62** 811 (Engl. Transl. 1995 *JETP Lett.* **62** 835)
[2] Hagen S J *et al* 1993 *Phys. Rev.* B **47** 1064
[3] Vinokur V M, Geshkenbein V B, Feigel'man M V and Blatter G 1993 *Phys. Rev. Lett.* **71** 1242
[4] Samoilov A V Legris A, Rullieralbenque F, Lejay P, Bouffard S, Ivanov Z G and Johansson L G 1995 *Phys. Rev. Lett.* **74** 2351
[5] Kang W N *et al* 1996 *Phys. Rev. Lett.* **76** 2993
[6] Spielman S, Parks B, Orenstein J, Nemeth D T, Ludwig F, Clarke J, Merchant P and Lew D J 1994 *Phys. Rev. Lett.* **73** 1537
[7] Geshkenbein V B and Larkin A I 1994 *Phys. Rev. Lett.* **73** 609
[8] Harris J M, Yan Y F, Tsui O K C, Matsuda Y and Ong N P 1994 *Phys. Rev. Lett.* **73** 1711
Harris J M, Ong N P and Yan Y F 1993 *Phys. Rev. Lett.* **71** 1455
[9] Samoilov A V 1994 *Phys. Rev.* B **49** 1246
[10] Graybeal J M, Luo J and White W R 1994 *Phys. Rev.* B **49** 12 923
[11] Samoilov A V 1997 *Phys. Rev. Lett.* **79** 4045
Smith A W and Lobb C J 1997 *Phys. Rev. Lett.* **79** 4044
These two papers comment on reference [5].
[12] Nelson D R and Vinokur V M 1992 *Phys. Rev. Lett.* **68** 2398
Nelson D R and Vinokur V M 1993 *Phys. Rev.* B **48** 13 060
[13] Blatter G, Feigel'man M V, Geshkenbein V B, Larkin A I and Vinokur V M 1994 *Rev. Mod. Phys.* **66** 1125
[14] Krishana K, Harris J M and Ong N P 1995 *Phys. Rev. Lett.* **75** 3529
[15] Bonn D A, Dosanjh P, Liang R and Hardy W N 1992 *Phys. Rev. Lett.* **68** 2390
Bonn D A *et al* 1993 *Phys. Rev.* B **47** 11 314
[16] Konczykowski M, Rullieralbenque F, Yacoby E R, Shaulov A, Yeshurun Y and Lejay P 1991 *Phys. Rev.* B **44** 7167
Civale L, Marwick A D, Worthington T K, Kirk M A, Thompson J R, Krusin-Elbaum L, Sun Y, Clem J R and Holtzberg F 1991 *Phys. Rev. Lett.* **67** 648
[17] van der Pauw L J 1958 *Philips Res. Rep.* **13** 1
van der Pauw L J 1961 *Philips Res. Rep.* **16** 187
[18] Beck R G, Farrel D E, Rice J P, Ginsberg D M and Kogan V G 1992 *Phys. Rev. Lett.* **68** 1594
[19] Yeh N-C, Jiang W, Reed D S, Kriplani U, Holtzberg F, Konczykowski M, Tsuei C C and Chi C C 1993 *Physica* A **200** 374
Yeh N-C, Reed D S, Jiang W, Kriplani U, Konczykowski M and Holtzberg F 1994 *Physica* C **235–240** 2659
[20] van Otterlo A, Feigel'man M, Geshkenbein V B and Blatter G 1995 *Phys. Rev. Lett.* **75** 3736
[21] Rietveld G, Chen N Y and van der Marel D 1992 *Phys. Rev. Lett.* **69** 2578
[22] Wei J Y T, Yeh N-C, Garrigus D F and Strasik M 1997 *Phys. Rev. Lett.* submitted
[23] Salamon M B, Shi J, Overend N and Howson M A 1993 *Phys. Rev.* B **47** 5520
Jeandupeux O, Schilling A, Ott H R and van Otterlo A 1996 *Phys. Rev.* B **53** 12 475
[24] Dorsey A T 1992 *Phys. Rev.* B **46** 8376
[25] We have used equations (9.76) and (9.100) of reference [13] to derive the critical current density j_c given in equation (3) for $B < B_{rb}$ and $B > B_{rb}$, respectively. The crossover field B_{rb} given in equation (4) is derived from equation (9.78) of reference [13]: $B_{rb}(T > T_{dl}) \approx B_\phi(r_r^2/2d_r^2)[\tilde{T}_{dl}/k_B T]^6$, where $\tilde{T}_{dl} = (2^{1/6}\varepsilon\varepsilon_0 r_r/\pi)\ln[d_r^2/(2\xi^2)]$, and $\tilde{T}_{dp}^r \approx (2\xi/\pi)\sqrt{\varepsilon_l\varepsilon_r}$ is assumed for the expression in equation (9.100) of reference [13]. In addition, the anisotropic line tension $\varepsilon_l = \varepsilon^2\varepsilon_0$ and the rod energy $\varepsilon_r \approx (r_r/2\xi)^2\varepsilon_0$ have been used in the analysis.
[26] Maki K 1968 *Prog. Theor. Phys. (Kyoto)* **39** 897
Maki K 1968 *Prog. Theor. Phys. (Kyoto)* **40** 193
[27] Thompson R S 1970 *Phys. Rev.* B **1** 327
[28] Nguyen A K, Sudbø A and Hetzel R E 1996 *Phys. Rev. Lett.* **77** 592
Nguyen A K and Sudbø A 1998 *Phys. Rev.* B **57** 3123
[29] Tesanović Z 1995 *Phys. Rev.* B **51** 16 204