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Vortex viscosity in $YBa_2Cu_3O_{7-\delta}$ at low temperatures

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With a bolometric technique, we have measured, in intense fields, the low-temperature surface resistance of both 90- and 60-K $YBa_2Cu_3O_{7-\delta}$ single crystals. In the former, the observed vortex viscosity $\eta_{\text{eff}}=5\times10^{-5}$ N s/m^2 exceeds by 2 orders of magnitude the viscosity in conventional superconductors. This corresponds to a normal-state resistivity of 0.4 $\mu\Omega$ cm, and a quasiparticle lifetime $\tau\sim6$ ps. (The corresponding numbers of the 60-K crystal are $\eta_{\text{eff}}=2.5\times10^{-6}$ N s/m^2 and $\tau=1.9$ ps at 3 K.) These lifetimes place $YBa_2Cu_3O_{7-\delta}$ firmly in the superclean regime where the lifetime broadening of core energy levels is much less than the energy spacing. We discuss how a very large Hall angle in this regime affects the analysis of surface resistance.

When a vortex line in a type-II superconductor responds to an oscillatory driving current, the frictional force is given by the damping viscosity (η), which in turn depends on the relaxation rate $1/\tau$ of quasiparticles trapped inside the vortex core.[1] There is strong interest in the low-temperature magnitude of τ in the high-T_c superconductors. If the width of the quasiparticle states ($\hbar/\tau$) turns out to be much smaller than the spacing $\hbar\omega_0$ between the lowest-energy states, the vortex system enters a new regime that was previously difficult to access in low-T_c superconductors.[2-4] Usually, the vortex viscosity is inferred from the surface resistance R_s measured in a microwave resonator with normal-metal walls. However, in $YBa_2Cu_3O_{7-\delta}$ (YBCO) this technique is restricted to temperatures above ~30 K because losses in the resonator walls limit the resolution.[5-7] (In $Bi_2Sr_2CaCu_2O_8$, measurements in a field have been extended[8] to ~6 K using a copper cavity held at 4.2 K.) In zero field, superconducting resonators have been used to extend R_s measurements to ~2 K,[9-11] but these techniques obviously cannot be extended to the vortex state. By using a bolometric technique capable of resolving sample absorption levels of ~0.1 nW at low temperatures, we have determined how R_s in 60 and 90 K crystals of YBCO changes with field up to 7 T at temperatures below 30 K. These measurements reveal an unusually large effective viscosity, and provide a firm determination of $\omega_0\tau$.

High-quality single crystals of 90-K YBCO were grown by a flux method. The as-grown crystals are microtwinned and display a sharp resistive transition at $T_c=91$ K (Fig. 1 inset). To produce oxygen-reduced crystals with high normal-state conductivity ($T_c=64$ K), we quenched[12] 90-K crystals from 650–670 °C. The crystal is glued to a sapphire substrate inside a waveguide with the static magnetic field normal to its basal plane ($\mathbf{B}\parallel c$). The incident microwave radiation (frequency $\omega/2\pi=30$ GHz and incident power between 0.3 and 30 mW) is amplitude modulated at a low frequency (7 Hz). Absorption of the microwave produces an oscillation in the sample's temperature T, which is detected by a small carbon bolometer. Care was taken to eliminate background absorption.[13] For calibration, we employed a reference sample (electropolished stainless steel of resistivity 50 $\mu\Omega$ cm) that is mounted on a second matched sapphire substrate. Comparison of the sample's bolometric signal with that of the reference provides a calibration of the sample's absorptivity up to 30 K. We have tested the technique[13] extensively on the layered superconductor $2H$-$NbSe_2$.

In the vortex state we may roughly estimate R_s in the two limits of large and negligible rf field penetration as follows. In terms of the vortex mobility $\mu_V(\omega)$ (defined[14] as the velocity divided by $J\phi_0$ where J is the current density and ϕ_0 the flux quantum), we may write the bulk resistivity ρ_f as $B\phi_0\mu_V$. In the strong-field limit when

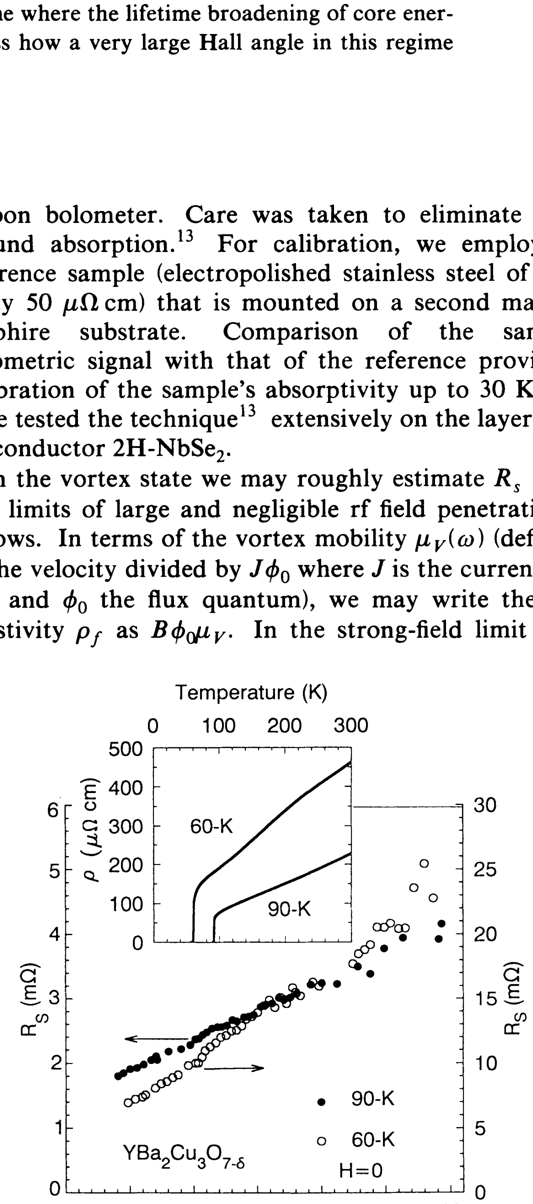

FIG. 1. The temperature dependence of R_s below 30 K in 60-K YBCO and 90-K YBCO (open and closed symbols, respectively) measured by absorption of 30-GHz radiation in zero dc magnetic field. The power absorbed is 10 nW at 4 K. The inset shows the dc in-plane resistivity of the crystals.

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the "flux-flow" skin depth δ_f greatly exceeds the penetration depth λ, we expect $R_s \sim \rho_f/\delta_f$ as in a normal metal $[\delta_f = \sqrt{(2\rho_f/\omega\mu_0)}$ with μ_0 the vacuum permeability]. In the opposite limit when the rf field penetration is restricted to λ, R_s is of the order of ρ_f/λ. Thus, R_s increases *linearly* with B for small penetration, but as $\sqrt{B}$ when the penetration greatly exceeds λ. According to Coffey and Clem,[14] the surface impedance is given by $Z(\omega,b) = i\omega\mu_0\lambda[(1-ib)/(1+is)]^{1/2}$, where s equals σ_1/σ_2 (the ratio of the real to imaginary parts of the conductivity). The reduced static field is defined by $b = B/B_\eta$, with $B_\eta = \omega\mu_0\lambda^2/\phi_0\mu_V$. In accord with the discussion above, Coffey and Clems' expression gives, in the high-field regime, $R_s(B) = \sqrt{(B\phi_0\mu_V\omega\mu_0/2)}$ and, in the weak-field regime ($b \ll 1$),

$$R_s(B) - R_s(0) = B\phi_0\mu_V/2\lambda \quad [R_s(0) = \omega^2\mu_0^2\lambda^3\sigma_1/2] \,. \quad (1)$$

The characteristic impedance $X_0 = \omega\mu_0\lambda$ sets the scale that determines the regime in which a measurement falls.

We first describe the surface resistance measured in zero field. Figure 1 shows that $R_s(0)$ in both crystals decreases nominally linearly with decreasing T, but appears to have a finite intercept at $T=0$. In the 90-K crystal, both the magnitude of the slope and the intercept are about 40% larger than the 2-GHz measurements of Bonn *et al.*[9] (after compensating for the ω^2 factor). The finite $R_s(0)$ at low temperatures has been interpreted as evidence for a d wave or a highly anisotropic s-wave gap parameter. The absorption in the 60-K crystal exceeds that in the 90-K crystal by a factor of 4 to 5. Most of this enhancement arises from the λ^3 factor in $R_s(0)$ [$\lambda = 2500$ (Ref. 15) and 1400 Å (Ref. 16) in the 60- and 90-K systems, respectively]. This implies that σ_1 has similar values in the two systems. Since the electronic dispersion is two dimensional, it is natural to express σ_1 in universal conductance units, viz. $(\sigma_1 d)/(e^2/h) = k_F l$ (where e^2/h is the universal conductance, k_F the Fermi wave vector, l the mean free path, and d the average interlayer spacing ~ 6 Å). At 5 K, the *total* $R_s(0)$ corresponds to $\sigma_1 = 2.6\times10^5$ and 1.6×10^5 $(\Omega\,\mathrm{cm})^{-1}$ (or $k_F l = 400$ and 245 in the 90- and 60-K crystals, respectively). These unusually large values of $k_F l$ suggest that the quasiparticles encounter very little scattering in the CuO_2 planes.

In conventional superconductors, dissipation in the vortex lattice moves rapidly into the high-field regime as soon as B exceeds ~ 0.1 T. Thus, R_s increases as $\sqrt{B}$ in fields in the few Tesla range. For example, in $NbSe_2$ the observed R_s at 3.2 K fits well to the high-field equation immediately preceding Eq. (1), and yields a mobility $\mu_V = 7.16\times10^6$ $m^2/N\,s$ (or a viscosity $\eta = 1/\mu_V = 1.40\times10^{-7}$ $N\,s/m^2$).[13] Moreover, the resistivity ρ_N calculated from η (using the Bardeen-Stephen[1] expression $\eta = B_{c2}\phi_0/\rho_N$) agrees closely with the measured dc resistivity (5 $\mu\Omega$ cm) just above T_c.

In contrast, fully-oxygenated 90-K YBCO displays an unexpectedly small surface absorption at low temperatures, even in intense fields (Fig. 2). At temperatures 17 K and lower, R_s changes by barely 1.5 mΩ as the field increases from 0 to 7 T. Since this is much smaller than the value of X_0 for this system ($=33$ mΩ), and the change in R_s is linear in B, we infer that we are in the weak-field regime [Eq. (1)]. Using the observed dR_s/dB in Eq. (1), we compute a mobility equal to 2.0×10^4 $m^2/N\,s$. It is useful to re-express this number as an "effective" viscosity η_{eff} which we *define* as the inverse mobility (η_{eff} is distinct from η when Hall-angle effects are pronounced, as shown below). Thus, at temperatures below 17 K, η_{eff} in 90-K YBCO equals 5.0×10^{-5} $N\,s/m^2$. This is by far the largest viscosity observed to date in any type-II superconductor (it exceeds the viscosity in $NbSe_2$ by a factor of 360). If we use the Bardeen-Stephen expression to convert η_{eff} to a low-temperature normal-state resistivity, viz. $\rho_N = B_{c2}\phi_0/\eta_{\mathrm{eff}}$ (assuming $B_{c2} = 100$ T), we find a rather small $\rho_N \sim 0.41$ $\mu\Omega$ cm. We remark that this is 8 times smaller than obtained by linearly extrapolating the normal-state resistivity down to 6 K (inclusion of impurity scattering further increases this discrepancy). The large viscosity implies a strongly suppressed scattering rate for quasiparticles trapped in the oscillating vortex core. From ρ_N and λ, we may also compute the quasiparticle lifetime using $\tau = \mu_0\lambda^2/\rho_N = \sim 6.0$ ps. In principle, this lifetime (of quasiparticles trapped in the vortex core) may be distinct from the lifetime inferred from zero-field measurements.[9] However, the measured values are of the same order of magnitude ($\tau = 2$ ps in Ref. 9).

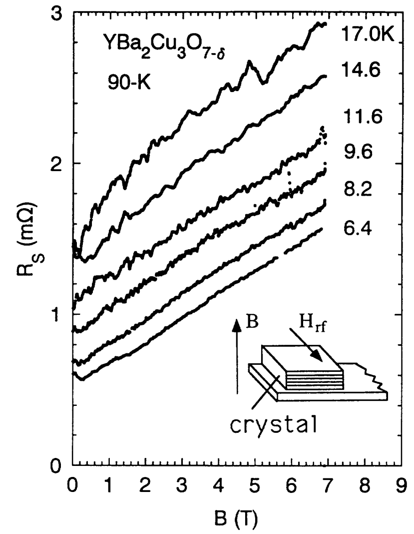

FIG. 2. The field dependence of R_s in 90-K YBCO at selected temperatures (taken with field decreasing). The variation of R_s is linear in B, at the 3 lowest temperatures. Hysteresis is small above 1 T. The inset shows the alignment of B and the microwave magnetic field H_{rf} relative to the crystal axes.

Turning now to the 60-K crystal, we find that its surface resistance differs from that in the 90-K crystal in several ways (Fig. 3). The scale of R_s is quite a bit larger than in Fig. 2 (at 7 T, R_s ranges from 9 mΩ at 2.7 K to 80 mΩ at 25 K). Comparing these values with the characteristic impedance of the 60-K system (for which $X_0 = 59$ mΩ), we find that R_s falls in the intermediate regime between the two limits. Unlike the data in Fig. 2, R_s now displays pronounced curvature at all temperatures for fields in the several Tesla range. Furthermore, the varia-

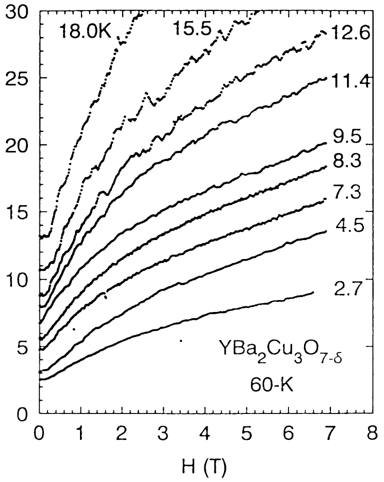

FIG. 3. The field dependence of R_s in 60-K YBCO taken in decreasing field (same alignment as in Fig. 2). In contrast with Fig. 2, R_s here is much larger and displays negative curvature vs B. The mobility is inferred from the derivative dR_s/dB at weak fields.

tion of R_s with temperature is more striking than in the 90-K system. This is particularly noticeable in the initial slope dR_s/dB (in weak fields dR_s/dB changes from 1.6 to 11 mΩ/T as T increases from 2.7 to 23 K). Using the initial slope in Eq. (1) to estimate the viscosity at each temperature, we find that it also changes by the same factor. The plot of η_{eff} in Fig. 4 shows that its temperature dependence is consistent with a power-law $1/T$ dependence. (As in the 90-K system, we may again convert the mobility to a resistivity and lifetime using the Bardeen-Stephen equation. The resistivity ρ_N varies from 4.1 to 27 $\mu\Omega$ cm between 2.7 and 23 K while τ changes from 1.9 to 0.3 ps, if we assume $B_{c2}\sim 50$ T. The values for ρ_N are again reduced from the extrapolated value in the inset in Fig. 1, but by a smaller factor than in the 90-K crystal.)

As mentioned above, it is natural to compare $\hbar/\tau$ with the energy-level spacing $\hbar\omega_0$ inside the vortex core. If the broadening of the core states is negligible compared with $\hbar\omega_0$ (i.e., $\omega_0\tau \gg 1$), the superconductor is in the "superclean" regime.[2-4] Dissipative processes and vortex dynamics are predicted to be different from the usual viscous regime. It was argued by Nozières and coworkers[2] that the vortex velocity should approach parallelism with **J** in the superclean limit (i.e., the Hall angle $\theta_H \to \pi/2$). A microscopic calculation by Kopnin and Kravtsov[3] (KK) shows that $\tan\theta_H$ diverges linearly with $\omega_0\tau$, when $\omega_0\tau \gg 1$. The possibility of "Hall tunneling" has also been discussed by Feigel'man *et al.*[4] It turns out that our experiment places the 90-K system firmly in this regime at low temperatures. However, to argue the case, we first need to discuss how a large-θ_H revises our analysis of the measured η_{eff}. Let us consider the equation for the vortex line velocity **u**,

$$\eta\mathbf{u}+\alpha\mathbf{u}\times\hat{\mathbf{z}}+\kappa\mathbf{x}=\phi_0\mathbf{J}\times\hat{\mathbf{z}}\ , \tag{2}$$

where η and α are the viscous drag and Hall drag coefficients, respectively, κ is the pinning parameter, and $\hat{\mathbf{z}}$ the unit vector parallel to **B** (we take $\mathbf{J}\parallel\hat{\mathbf{x}}$). In the limit $\omega \gg \kappa/\eta$, Eq. (2) may be solved for the dissipative component of the mobility μ_{Vy}, and, hence, we obtain $\eta_{\text{eff}}=(\eta^2+\alpha^2)/\eta$. The Hall angle (the angle between **u** and $\hat{\mathbf{y}}$) is given by $\tan\theta_H=\alpha/\eta$. When $\alpha/\eta \gg 1$, **u** approaches alignment with **J**, and μ_{Vy} decreases rapidly. In the large-θ_H limit, KK's calculations[3] show that $\alpha \to n_s e\phi_0$ while $\eta \to 1.36 n_s e\phi_0/\omega_0\tau\ln(\Delta/T)$. Substituting into η_{eff}, we have

$$\eta_{\text{eff}}=0.74(n_s e\phi_0)\omega_0\tau\ln(\Delta/T)\quad(\alpha \gg \eta)\ . \tag{3}$$

From $\omega_0=\Delta^2/\hbar\varepsilon_F$, we obtain $n_s e\phi_0\omega_0\tau=(4/\pi^2)B_{c2}\phi_0/\rho_N$ (where Δ is the gap parameter and ε_F the Fermi energy, and $\rho_N=m^*/n_s e^2\tau$). Thus, Eq. (3) is similar to using the Bardeen-Stephen expression for η_{eff}, apart from a weakly T-dependent factor of order 1. Hence, *the value of τ obtained by simply inserting η_{eff} into the Bardeen-Stephen expression is within a factor of 2* of the actual value computed using equations appropriate for large θ_H.

We are now in a position to determine $\omega_0\tau$. As a preliminary estimate we note that, in the 90-K system, $\omega_0=(4/\pi^2)eB_{c2}/m^* \sim 2.9\times10^{12}$ rad/s (or 22 K), so that $\omega_0\tau \sim 17$. (We take the effective mass ratio $m^*/m_0=2.4$. This estimate for ω_0 comes out much smaller than the value $\omega_0=110$ K derived from a recent far-infrared transmission experiment.[17]) Equation (3) gives a slightly smaller value, $\omega_0\tau=14$, for the 90-K sample, and $\omega_0\tau=2.1$ for the 60-K sample at 3 K. Either of these estimates confirms that 90-K YBCO is firmly in the "superclean" regime below $\sim$15 K, while 60-K YBCO enters this regime below $\sim$3 K. A recent dc experiment that offers independent support for this scenario is the observation[18] that the flux-flow Hall angle θ_H in 60-K YBCO crystals undergoes a rapid growth below 40 K ($\tan\theta_H$ reaches -0.6 at 13 K in a 23-T field). The Hall-angle data are actually consistent with a $1/T$ dependence for $|\tan\theta_H|$, and extrapolate to a value 2–4 below 4 K. In 90-K YBCO the Hall angle has not been measured below

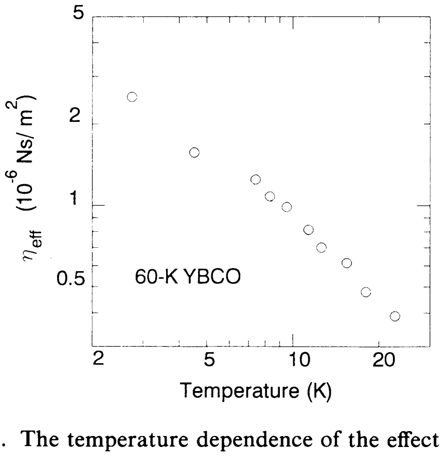

FIG. 4. The temperature dependence of the effective viscosity in 60-K YBCO inferred from the surface resistance data in Fig. 3. The straight line has a slope of -1. (η_{eff} in the 90-K crystal is almost T independent below 15 K.)

70 K because pinning effects are much stronger. However, the existence of a very large Hall angle is consistent with the field-induced "rotation" of the flux-flow pattern detected recently[19] in the remanent magnetization of 90-K crystals below 30 K.

Finally, we comment on the neglect of the pinning term in Eq. (2). A rough estimate of the pinning frequency in 90-K YBCO by Morgan *et al.*[7] places it between 10 and 20 GHz near 30 K. The pinning frequency in the 60-K system has not been reported, but we infer that it is at least a factor of 10 smaller because flux flow is readily observed[18] at temperatures as low as 11 K. Thus, our measurements are comfortably in the free-flow regime for the 60-K system. In the 90-K system, measurements above 30 GHz are desirable, but we estimate that $\eta_{\rm eff}$ inferred from Fig. 2 is within 15% of the free-flow value. Flux pinning also leads to strong hysteresis in the flux distribution within the crystal. However, since the experiment probes absorption within a few microns of the surface, it is not sensitive to flux inhomogeneities in the bulk.[20]

In conclusion, bolometric studies of the vortex absorption in YBCO reveals an unusually large viscosity at low temperatures. The long relaxation time τ of quasiparticles in the vortex core ($\sim$6 ps in 90-K YBCO) implies that the parameter $\omega_0\tau$ is roughly 14–17. This places YBCO firmly in the "superclean" regime. The effect of an enhanced Hall angle was considered and incorporated in the analysis of the viscosity.

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[13] Cyclotron resonance absorption signals in the Ag grains of the contact pads on the bolometer are 3–5 times larger than the sample signal. To eliminate this, we place the bolometer outside the waveguide at the end of the sapphire substrate. The smallest resolvable temperature increment is $\sim$0.1 mK (this corresponds to a power of 0.1 nW at 5 K and 20 mW at 30 K). The power absorbed in the 90-K crystal ($\sim$10 nW at 4 K) implies a surface field $H_{\rm rf}$ of $\sim$9 A/m and a $J\sim6500$ A/cm^2. Using the value of $\eta_{\rm eff}$, we calculate the amplitudes $u\sim0.27$ cm/s, and $x\sim10^{-4}$ Å. Y. Matsuda and N. P. Ong (unpublished).

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[20] The data shown in Figs. 2 and 3 are taken in decreasing field. Data taken in increasing field agree to within the measurement uncertainty when the field exceeds 1 T. Below 1 T, flux remanence causes a slight hysteresis which does not affect the value of $\eta_{\rm eff}$ inferred from the high-field slope.