Dissipative and Hall quantum creep in $YBa_2Cu_3O_{7-\delta}$ thin films

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From dynamic relaxation measurements of the decay of supercurrents in $YBa_2Cu_3O_{7-\delta}$ films with thicknesses between 1.2 and 150 nm we determine the correlation length $L_c(0)$ (the length of the tunneling vortex segment at $T=0$ K) to be 2.2 nm and show that quantum creep occurs in a transition regime where Hall tunneling is as important as dissipative tunneling.

Soon after the discovery of high-T_c superconductivity Yeshurun and Malozemoff[1] reported on the existence of giant flux creep in high-temperature superconductors. Giant flux creep which has been found in all layered superconductors arises from the thermally activated motion of vortices from one metastable configuration to a neighboring one. The probability for such a hopping process is proportional to $\exp[-U(j,T,B_e)/kT]$, where $U(j,T,B_e)$ is the activation energy which depends on the current j, external field $B_e=\mu_0 H_e$ and temperature T. At low temperature $U(j,T,B_e)/kT$ diverges and the hopping probability vanishes. However, several experiments demonstrated that substantial relaxation was still present in the millikelvin regime. One of the most convincing proofs of the existence of this quantum creep was given by Fruchter *et al.*[2] who found a temperature independent relaxation rate below 1 K in an $YBa_2Cu_3O_{7-\delta}$ single crystal. Evidence for the existence of quantum creep has also been found in many other investigations on high-T_c superconductors,[3–7] heavy fermions,[3] organic superconductors,[4] and Chevrel phases.[8]

In contrast to thermally activated flux motion which depends essentially on the height of the activation energy barrier, quantum creep depends on the time spent under the energy barrier during the tunneling of a vortex segment of length L_c.[9] Quantum creep is, therefore, inherently related to the dynamics of a vortex segment, which according to Kopnin *et al.*[10,11] is described by the following equation of motion:

$$\eta\vec{v}_v+\alpha\vec{v}_v\times\hat{z}=\Phi_0 L_c\vec{j}_s\times\hat{z}+\vec{F}_{\rm pin}, \tag{1}$$

where $\vec{v}_v$ is the vortex velocity, Φ_0 the flux quantum, j_s the current density, and $\hat{z}$ a unit vector parallel to the vortex. The first term on the left-hand side of Eq. (1) represents the viscous drag and the second term is the Hall contribution.

Until recently quantum creep experiments have always been interpreted by assuming that dissipative effects were dominant, i.e., $\eta\gg\alpha$. However, Feigel'man *et al.*[12] proposed recently that high-T_c superconductors might be in the superclean limit and that quantum creep is essentially determined by the Hall term in Eq. (1). Their proposition was based on an estimate of $\rho_n(0)$ by using a linear extrapolation of $\rho_n(T\geq T_c)$ data which leads to a low-temperature resistivity $\rho_n(0)\approx 10$ $\mu\Omega$ cm and a mean free path $l\approx 70$ nm, which is indeed much larger than $\xi E_F/\Delta$, where ξ is the coherence length, E_F the Fermi energy, and Δ the superconducting gap.

The purpose of this paper is to show that at low temperatures the high-T_c superconductor $YBa_2Cu_3O_7$ is (i) *neither in the purely dissipative regime nor in the superclean limit*, but in an intermediate regime where both Hall and dissipative terms contribute to the tunneling of vortices and (ii) that L_c at $T=0$, i.e., $L_c(0)$ is much smaller than near the irreversibility line.[13,14] To arrive at these conclusions we measured the relaxation rate Q of superconducting currents in $YBa_2Cu_3O_7$ films of thicknesses D ranging from 1.2 nm (1 unit cell) to 150 nm as a function of temperature in magnetic fields up to 7 T. In this work we concentrate on the low-temperature relaxation.

The thin films were grown by dual target sputtering[15] as 8 blocks of $YBa_2Cu_3O_7$ (YBCO) of $N=1$, 2, 3, 4, and 8 unit cells separated from each other by 9.6 nm of highly insulating $PrBa_2Cu_3O_7$ (PrBCO) layers. A $N=3$ sample corresponds thus to a sample of 8 blocks made of 3.6 nm YBCO and 9.6 nm PrBCO each. As shown by Brunner *et al.*[13] 9.6 nm thick PrBCO layers guarantee a complete decoupling of the YBCO layers. The use of multilayers improves the signal-to-noise ratio by a factor of 8, which is required for measurements on the thinnest samples. ($N=1$; $D=1.2$ nm.) Representative inplane resistive transitions for $N=1,2,3$ samples and a 150 nm film ($N\cong 125$) are shown in Fig. 1. The T_c values at 10% of the transition are 23, 51, 61, and 90 K for the $N=1,2,3$ samples and the 150 nm film, respectively.

As discussed by Jirsa *et al.*[16] relaxation effects in thin films are most advantageously determined by measuring the dynamic relaxation rate $Q\equiv d\ln j_s/d\ln(dB_e/dt)$, i.e., by measuring the superconducting current j_s flowing in a film as a function of the sweeprate dB_e/dt of the external field. Since j_s is directly proportional to the magnetic moment M_s which can be measured by means of a sensitive capacitance torque magnetometer,[17] Q is determined from torque hysteresis loops recorded at various sweeprates. For all samples we found that j_s varies linearly with $\ln(dB_e/dt)$. This is clearly visible in Fig. 2 for the $N=1$ sample, where j_s decreases by the same amount whenever the sweeprate is halved. This implies that

$$j_s=j_c\left[1-a\ \ln\left(\frac{(dB_e/dt)_{\rm max}}{dB_e/dt}\right)\right], \tag{2}$$

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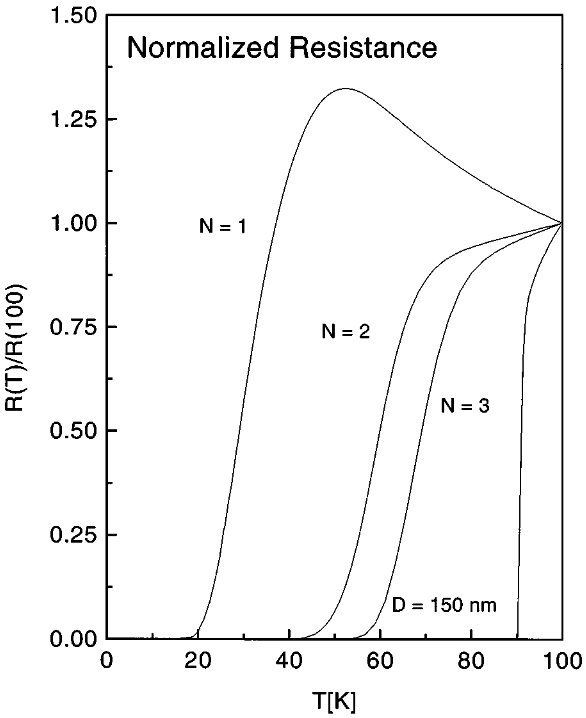

FIG. 1. Resistive transitions of representative YBCO/PrBCO multilayers used for the creep measurements. The resistivity is normalized at its value at 100 K. The labels $N=1$, 2, and 3 refer to the number of unit cells per YBCO layer. The transition at 90 K corresponds to an YBCO film of 150 nm thickness ($N\cong 125$). The resistivity values are ρ_n (100 K)=317, 190, 138, and 127 $\mu\Omega$ cm for the $N=1,2,3$ and the 150 nm film, respectively.

where $(dB_e/dt)_{\max}$ is the maximum sweep rate compatible with flux creep (for $dB_e/dt > (dB_e/dt)_{\max}$ the vortex system would be in the flux-flow regime). The functional dependence in Eq. (2) implies that the effective Euclidean action for tunneling S_{eff} is proportional to $S_{\text{eff}} \propto (1-j_s/j_c)$. Although

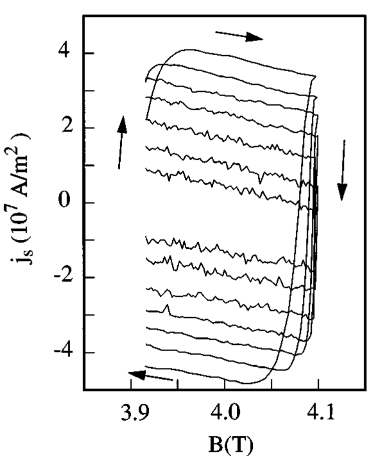

FIG. 2. Torque hysteresis loops near $B_e=4$ T of a $N=1$ YBCO/PrBCO multilayer at 2.1 K. The most hysteretic loop corresponds to a sweeprate $dB_e/dt=40$ mT/s. The other loops are obtained by successively reducing the sweeprate by a factor 2. Similar results, but with a much better signal-to-noise ratio, have been measured in all other (thicker) samples.

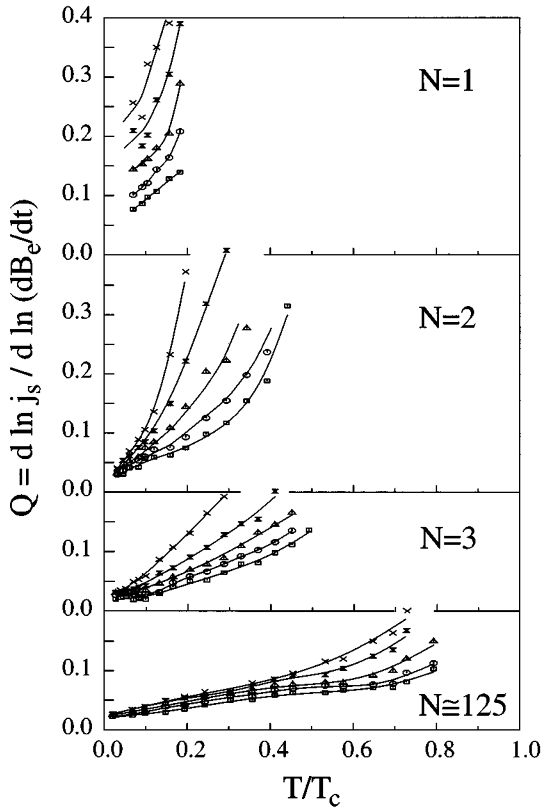

FIG. 3. Dynamic relaxation rate Q of $N=1,2,3$ YBCO/PrBCO multilayers and of a 150 nm ($N\cong 125$) thick YBCO film, determined from hysteresis loops such as in Fig. 2 for $B_e=0.5$, 1, 2, 4, and 7 T (from bottom to top in each panel). For clarity the curves have been plotted as a function of $t=T/T_c$. The superconducting transition temperatures are $T_c(N=1)=23$ K, $T_c(N=2)=51$ K, $T_c(N=3)=61$ K, and $T_c(D=150\text{ nm})=90$ K. Similar results have been obtained for $N=4$ and 8 multilayers.

Blatter *et al.*[18] showed that the exponent n for the current dependence $(1-j_s/j_c)^n$ can be different from 1 we found that the data for all the films investigated here could be well reproduced with $n\cong 1$.

The slope $aj_c = dj_s/d\ \ln(dB_e/dt)$ in Eq. (2), when normalized to j_s at a certain sweep rate, is by definition equal to Q at this particular sweep rate. In this work the Q values are evaluated at $dB_e/dt=40$ mT/s. The measured relaxation rates $Q(T)$ for the films with $N=1$, 2, 3, and 125 are displayed versus temperature for $B_e=0.5$, 1, 2, 4, and 7 T in Fig. 3. Similar results are found for film thicknesses of 4.8 and 9.6 nm. In the low-temperature limit these data exhibit two most remarkable properties: (i) for all films with $N\geqslant 2$ the extrapolated low-temperature relaxation rate $Q(0)$ is typically 0.02 depending only slightly on the magnetic field for 0.5 T$\leqslant B_e \leqslant$7 T and (ii) for the $N=1$ sample the relaxation rate is, however, significantly larger for all magnetic fields. The almost constancy of $Q(0)$ for the $N\geqslant 2$ films is surprising since, as shown below, both in the dissipative and the superclean limit $Q\propto 1/L_c(0)$ as α and η are both proportional to $L_c(0)$. If $L_c(0)$ had been as large as the value found by Brunner *et al.*,[13] i.e., $L_c\approx 45$ nm near the irreversibility temperature T_{irr}, we would have had $L_c(0)>D$ for all thin films ($N\leqslant 8$) investigated in this work and, consequently, since D would be smaller than $L_c(0)$, $Q(0)\propto 1/D$. This would have led to a variation in $Q(0)$ by at least a factor of 4 between the samples with $N=1$ and $N=8$. Since this is not observed we conclude that $L_c(0)$ is smaller (or equal) to the thickness D for the samples with $N\geqslant 2$ while $L_c(0)>D$ in the $N=1$ sample.[19] We conclude that a 3D-2D crossover occurs when N is decreased from 2 to 1. Furthermore, since for the $N=2$ sample $Q(T)$ increases rapidly with increasing temperature at low $t=T/T_c\approx 0.2$ we conclude that $L_c(0)$ is only slightly smaller than 2.4 nm. An estimate based on $L_c(t)=L_c(0)(1+t^2)/(1-t^2)$ (Ref. 14) leads to $L_c(0)=2.2$ nm. The value $L_c(0)\approx 2.2$ nm is consistent with an estimate based on the following expression:[18]

$$L_c \cong \left(\frac{\xi \Phi_0 \ln\kappa}{4\pi\mu_0 \lambda^2 \gamma^2 j_c} \right)^{1/2}. \tag{3}$$

With $\xi=1.5$ nm, $\kappa=100$, $\lambda=150$ nm, $\gamma=7$, and $j_c=8\times 10^{10}$ A/m^2 which are appropriate for the 150 nm YBCO film at low temperature[14] one finds $L_c(0)=3.2$ nm. As discussed in Ref. 14 the large difference between L_c $(T\approx T_{\rm irr})\approx 45$ nm and our value $L_c(0)\approx 2.2$ nm is essentially due to the temperature dependence of the various physical quantities in Eq. (3).

For a quantitative discussion of quantum creep in thin films we need an expression for $Q(0)$ as a function of α and η. As discussed by Kopnin *et al.*[11] and Blatter *et al.*,[18] α and η depend on $\omega_B\tau$ as

$$\alpha(\omega_B\tau)=\pi\hbar n_s L_c(0)\,\frac{(\omega_B\tau)^2}{1+(\omega_B\tau)^2}=\omega_B\tau\,\eta(\omega_B\tau), \tag{4}$$

where the transport relaxation time $\tau=m/n_s e^2\rho_n(0)$ is related to the normal state resistivity $\rho_n(0)$ at zero temperature and the density of charge carriers n_s. The energy separation $\hbar\omega_B$ between low lying levels in the vortex core is approximately given by $\hbar\omega_B\simeq\hbar^2/2m\xi^2$.

In the dissipative limit, $\omega_B\tau\ll 1$, the viscous drag coefficient η is given by the Bardeen-Stephen expression[20] at low temperatures

$$\eta_0=\eta(\omega_B\tau\ll 1)\cong \frac{\Phi_0 B_{c2} L_c(0)}{\rho_n(0)}=\frac{\pi\hbar^2}{2e^2}\,\frac{L_c(0)}{\rho_n(0)}\,\frac{1}{\xi^2}. \tag{5}$$

In the superclean limit, $\omega_B\tau\gg 1$ and $\alpha_\infty=\alpha(\omega_B\tau\to\infty)=\pi\hbar n_s L_c(0)$. The effect of the averaged effective pinning force $\vec{F}_{\rm pin}$ in Eq. (1) is a renormalization of the viscous drag coefficient while the Hall coefficient α remains unchanged.[21]

In the purely dissipative regime the quantum creep relaxation rate Q_D can readily be evaluated from the tunneling probability derived by Caldeira and Leggett[5,22] to be $Q_D=A\hbar j_c/\eta_0 x_{\rm hop}^2 j_s$, where $2x_{\rm hop}$ is the distance separating the positions of the vortex segment before and after tunneling. For a cubic potential $U(x)=3U_0(x/x_0)^2(1-2x/3x_0)$ the results of Larkin and Ovchinnikov[23] lead to $A\approx 1$ and $x_0=x_{\rm hop}[1-(j_s/j_c)^2]^{1/2}\simeq\sqrt{2}x_{\rm hop}[1-j_s/j_c]^{1/2}$ for $j_s\approx j_c$. Here j_c is the critical current for which the energy barrier between two vortex configurations vanishes. For $j_s\leqslant j_c$ and noting that $x_{\rm hop}$ is of the order of ξ this leads to

$$Q_D\cong\frac{\hbar}{\eta_0\xi^2}\,\frac{j_c}{j_s}. \tag{6}$$

For the superclean regime Feigel'man *et al.*[12] calculated that the Hall-relaxation rate is given by

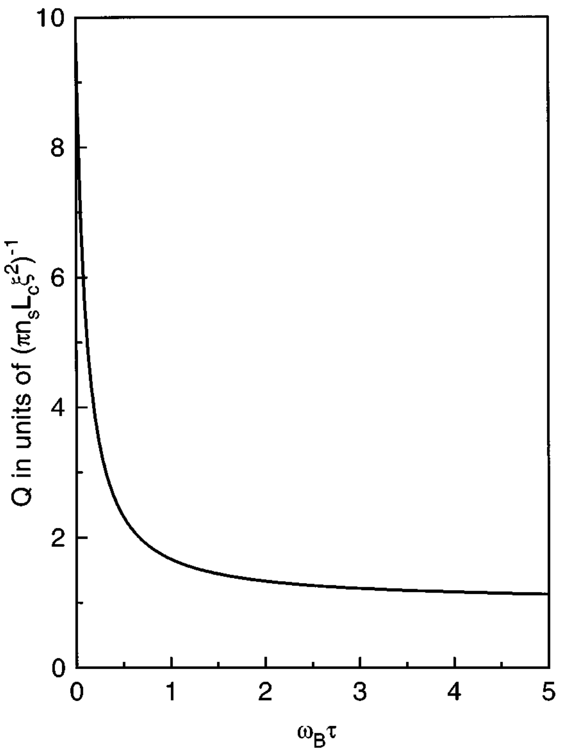

FIG. 4. Dependence of the quantum creep relaxation rate $Q(0)$ [in units of $(\pi n_s L_c(0)\xi^2)^{-1}$] on $\omega_B\tau=\alpha/\eta$, according to Eq. (8). In the superclean limit ($\omega_B\tau\to\infty$) and in the dissipative limit ($\omega_B\tau\ll 1$) Eq. (8) reduces to Eqs. (6) and (7), respectively.

$$Q_H\approx\frac{\hbar}{\alpha_\infty\xi^2}\,\frac{j_c}{j_s}. \tag{7}$$

From Stephen's treatment of quantum tunneling of vortex lines, it is possible to obtain an expression for arbitrary values of $\omega_B\tau$. To logarithmic accuracy, we find that [see Eq. (20) in Ref. 24]

$$Q(T=0,\omega_B\tau)=\frac{1}{\pi n_s L_c(0)\xi^2}\left[\frac{1}{\omega_B\tau}+\frac{1}{2}+\frac{1}{\pi}\arctan(\omega_B\tau)\right] \tag{8}$$

and we recover Eq. (6) in the limit $\omega_B\tau\ll 1$ and Eq. (7) in the limit $\omega_B\tau\gg 1$. In Eq. (8) we have taken $j_c/j_s=1$ which is appropriate at low temperatures. The function between square brackets, which is plotted in Fig. 4, has the very interesting property to be essentially constant and equal to 1 for $\omega_B\tau>1$. This means that even if $\omega_B\tau$ varies from sample to sample, $Q(0)$ remains essentially constant as long as $\omega_B\tau>1$. We believe that this is the explanation[25] of the remarkably similar $Q(0)$ values which have been found in other high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_8$ (Ref. 6) and $Tl_2Ba_2CaCu_2O_8$.[7] The regime in which quantum creep occurs in $YBa_2Cu_3O_7$ films can be identified by evaluating $\pi Q(0)n_s L_c(0)\xi^2$. Using $Q(0)=0.02$, $L_c(0)=2.2$ nm, as determined in this work and $n_s=5\times 10^{27}$ m^{-3} from Refs. 26–30 and $\xi=1.5$ nm we obtain $\pi Q(0)n_s L_c(0)\xi^2=1.6$ which corresponds to $\omega_B\tau=1.3$. This value of $\omega_B\tau$ and the corresponding Hall angle $\Theta_H=\arctan(\alpha/\eta)=\arctan(\omega_B\tau)$

≈50° are indicative of a creep regime intermediate between a purely dissipative and a superclean Hall quantum creep regime. This conclusion is further supported by the observation that $Q(0)$ increases as soon as oxygen is removed from $YBa_2Cu_3O_x$ films.[31] When x is lowered below 7, $\rho_n(0)$ increases and $\omega_B\tau$ decreases. A simultaneous increase of $\omega_B\tau$ and decrease of $Q(0)$ is impossible, since in the superclean limit $Q(0)$ is virtually independent of $\omega_B\tau$, as shown in Fig. 4.

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