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Dissipative and Hall quantum creep in YBa$_2$Cu$_3$O$_{7-\delta}$ thin films

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From dynamic relaxation measurements of the decay of supercurrents in YBa$_2$Cu$_3$O$_{7-\delta}$ 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$^7$ 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 $\exp[-U(j,T,B_c)/kT]$, where $U(j,T,B_c)$ is the activation energy which depends on the current $j$, external field $B_c=\mu_0H_c$, and temperature $T$. At low temperature $U(j,T,B_c)/kT$ 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 a YBa$_2$Cu$_3$O$_{7-\delta}$ 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,$^8$ 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:

$$\eta \ddot{\vec{v}}_v + \alpha \dot{\vec{v}}_v \times \hat{z} = \Phi_0 L_c j_s \hat{z} + \vec{F}_{\text{pin}},$$

(1)

where $\vec{v}_v$ is the vortex velocity, $\Phi_0$ 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 $\rho_a(0)$ by using a linear extrapolation of $\rho_a(T=T_c)$ data which leads to a low-temperature resistivity $\rho_a(0)\approx 10 \mu\Omega$ cm and a mean free path $l\approx 70$ nm, which is indeed much larger than $\xi E_F/\Delta$, where $\xi$ is the coherence length, $E_F$ the Fermi energy, and $\Delta$ the superconducting gap.

The purpose of this paper is to show that at low temperatures the high-$T_c$ superconductor YBa$_2$Cu$_3$O$_7$ 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$_2$Cu$_3$O$_7$ 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$_2$Cu$_3$O$_7$ (YBCO) of $N=1$, 2, 3, 4, and 8 unit cells separated from each other by 9.6 nm of highly insulating PrBa$_2$Cu$_3$O$_7$ (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.$^{15}$ 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 in-plane resistive transitions for $N=1,2,3$ samples and a 150 nm film ($N=125$) 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 Jirska et al.$^{16}$ relaxation effects in thin films are most advantageously determined by measuring the dynamic relaxation rate $Q=d \ln J/s/d \ln (dB_s/dt)$, i.e., by measuring the superconducting current $J_s$ flowing in a film as a function of the sweeprate $dB_s/dt$ 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 $\ln (dB_s/dt)$. 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

$$J_s = J_{c1} \left[ 1 - \alpha \ln \left( \frac{dB_s/dt}{dB_s/dt_{\max}} \right) \right],$$

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

The slope \( a_{j_c}=d j_c/d \ln(d B_e/d t) \) in Eq. \(~2\), when normalized to \( j_c \) 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 \( d B_e/d t=40 \) 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 have been obtained for \( N=4 \) and 8 multilayers.

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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 $N \geq 2$ while $L_c(0) > D$ in the $N=1$ sample.\(^{18}\) We conclude that a 3-D-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 $L_c(0) = 2.2$ nm is consistent with an estimate based on the following expression:\(^{18}\)

$$L_c \approx \left( \frac{\xi \Phi_0}{4 \pi \mu_0 \lambda \gamma f_c} \right)^{1/2}.$$  

(3)

With $\xi = 1.5$ nm, $\kappa = 100$, $\lambda = 150$ nm, $\gamma = 7$, and $j_\perp = 8 \times 10^{10}$ $\text{A/m}^2$ 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 $L_c(0) (T \approx 0.5 T_c) = 45$ nm and our value $L_c(0) = 2.2$ 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 $\alpha$ and $\eta$. As discussed by Kopnin et al.\(^{11}\) and Blatter et al.\(^{18}\) $\alpha$ and $\eta$ depend on $\omega_B \tau$ as

$$\alpha(\omega_B \tau) = \pi \hbar n_c L_c(0) \left( \frac{\omega_B \tau}{1 + (\omega_B \tau)^2} \right) = \omega_B \tau \eta(\omega_B \tau),$$  

(4)

where the transport relaxation time $\tau = n_s e^2 \rho_n(0)$ 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 $\hbar \omega_B = \hbar^2 / 2 \eta f_c$.

In the dissipative limit, $\omega_B \tau \ll 1$, the viscous drag coefficient $\eta$ is given by the Bardeen-Stephen expression\(^{16}\) at low temperatures

$$\eta_0 = \eta(\omega_B \tau << 1) \approx \frac{\Phi_0 B_c L_c(0)}{\rho_n(0)} = \frac{\pi \hbar^2 L_c(0)}{2 e^\gamma \rho_n(0)} \xi.$$  

(5)

In the superclean limit, $\omega_B \tau \approx 1$ and $\alpha_\infty = \alpha(\omega_B \tau \rightarrow \infty) = \pi \hbar n_c L_c(0)$. The effect of the averaged effective pinning force $F_{\text{pin}}$ in Eq. (1) is a renormalization of the viscous drag coefficient while the Hall coefficient $\alpha$ remains unchanged.\(^{18}\)

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\(^{12,22}\) to be $Q_D = A h j_\perp \eta_0 \lambda n_{\text{hop}}$, where $2 x_{\text{hop}}$ is the distance separating the positions of the vortex segment before and after tunneling. For a cubic potential $U(x) = 3 U_\phi(x_0)^2 (1 - 2 x_0 / 3 x_0)$ the results of Larkin and Ovchinnikov\(^{23}\) lead to $A \approx 1$ and $x_0 = x_{\text{hop}} (1 - j_\perp / j_c)^{3/2} \approx \sqrt{2 x_{\text{hop}} (1 - j_\perp / j_c)^{3/2}}$ for $j_\perp \approx j_c$. Here $j_c$ is the critical current for which the energy barrier between two vortex configurations vanishes. For $j_\perp \approx j_c$ and noting that $x_{\text{hop}}$ is of the order of $\xi$ this leads to

$$Q_D = \frac{\hbar}{\eta_0 f_c} \frac{j_c}{j_s}.$$  

(6)

For the superclean regime Feigel’man et al.\(^{12}\) calculated that the Hall-relaxation rate is given by

$$Q(0) = \left[ \frac{1}{\omega_B \tau} + \frac{1}{\pi} \arctan(\omega_B \tau) \right].$$  

(8)

and we recover Eq. (6) in the limit $\omega_B \tau \ll 1$ and Eq. (7) in the limit $\omega_B \tau \approx 1$. In Eq. (8) we have taken $j_\perp / j_c = 1$ 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 of the remarkably similar $Q(0)$ values which have been found in other high-$T_c$ superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Ref. 6) and Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$.\(^{7}\) The regime in which quantum creep occurs in YBa$_2$Cu$_3$O$_7$ films can be identified by evaluating $\pi Q(0) n_c L_c(0) \xi^2$. 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 $\pi Q(0) n_c L_c(0) \xi^2 = 1.6$ which corresponds to $\omega_B \tau = 1.3$. This value of $\omega_B \tau$ and the corresponding Hall angle $\Theta_H = \arctan(\alpha/\eta) = \arctan(\omega_B \tau)$
\( \sim 50^\circ \) 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 \( \text{YBa}_2\text{Cu}_3\text{O}_x \) films. When \( x \) is lowered below 7, \( \rho_0(0) \) 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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19. The difference in behavior between the \( N=1 \) and the \( N \geq 2 \) samples cannot be attributed to structural defects since our contactless relaxation rate measurements, in sharp contrast to transport measurements, are independent of the current paths in the sample, i.e., the current is not forced to flow through weak links. Furthermore we found that the current-voltage curves determined from our \( j_s \) versus \( dB_e/dt \) measurements exhibit the same 2D characteristics as the results of Dekker et al. [Phys. Rev. Lett. 69, 2717 (1992)] obtained in ultrathin YBCO films.
25. The condition \( \omega_B \tau > 1 \) is of course not sufficient. However, in all high-\( T_c \) superconductors \( L_2(0) \) is expected to be of the order of one or two unit cells and since the London penetration depths determined experimentally are always of the order of 150 nm, \( n_s \) is also expected to vary little from one material to the other.