PHYSICAL REVIEW B, VOLUME 63, 054509

Evidence for vortex tunnel dissipation in deoxygenated $YBa_2Cu_3O_{6.4}$ thin films

Z. Sefrioui,[1] D. Arias,[1,*] F. Morales,[2] M. Varela,[1,†] C. León,[1] R. Escudero,[2] and J. Santamaria[1]
[1]GFMC, Departamento de Fisica Aplicada III, Universidad Complutense de Madrid, 28040 Madrid, Spain
[2]Instituto de Investigaciones en Materiales, Universidad Nacional Autonoma de Mexico,
Apartado Postal 70-360, Mexico, D.F. 04510, Mexico

(Received 3 October 2000; published 8 January 2001)

We report on transport and magnetic relaxation measurements of deoxygenated $YBa_2Cu_3O_{7-\delta}$ thin films. Strongly oxygen depleted samples with $\delta=0.6$ are produced to ensure the pure two-dimensional nature of the vortex system. Linear resistivity shows a temperature dependence according to $\rho_{lin}\propto\exp[-(T_0/T)^p]$. T_0 takes a value of 230 ± 10 K over the whole field range, and p changes from 1 ± 0.03 at 2 T to 0.70 ± 0.03 at 8 T. For fields higher than 4 T, dissipation in the linear regime (low current densities) is dominated by quantum variable range hopping (VRH) of vortices. At high current densities and low temperatures, nonlinear dissipation takes place by quantum creep, characterized by a temperature-independent resistivity and by a saturation of the magnetic relaxation rate.

DOI: 10.1103/PhysRevB.63.054509 PACS number(s): 74.72.Bk, 74.60.Ge, 74.50.+r

The possibility of quantum tunneling of vortices has been a subject of theoretical interest in recent years. Macroscopic quantum tunneling of flux lines in superconducting quantum interference devices (SQUID) was analyzed by Caldeira and Leggett.[1] Various experimental works[2–4] have shown nonzero values for the low-temperature magnetic relaxation rate, suggesting that the classical thermally activated regime might cross over into a quantum one in which vortex motion would proceed by tunneling. The possibility of vortex tunneling in thin superconducting films was proposed by Glazman and Fogel,[5] but temperature-independent resistance has only been observed in low-T_c ultrathin films and multilayers.[6–8] Very recently, experimental evidence for dissipation by quantum creep has been presented in $Y_{1-x}Pr_xBa_2Cu_3O_7$ in the nonlinear regime[9] by flux transformer measurements,[10] where a saturation of the resistance is observed in a thin decoupled layer. These experiments[6–8,10] suggest that the observation of vortex tunneling is favored in two-dimensional (2D) systems.

The process of quantum creep in bulk superconductors has been theoretically analyzed by Blatter *et al.*[11] in the frame of the collective pinning theory,[12] showing that, in the limit of strong dissipation (nonlinear regime) and for moderate magnetic fields, the single vortex tunneling rate is determined by the ratio $(e^2/\hbar)\rho_n/\xi$ of the normal-state resistivity and the superconducting coherence length. Strong tunneling is expected when this ratio is equal or greater than one. Therefore, the high normal-state resistivity and the short coherence length of the high-T_c superconductors (HTS) favor this mechanism at low temperatures. According to the collective quantum creep theory,[10,13] for a 3D vortex system, in-plane correlations control the 3D vortex bundle volume, which are the tunneling objects. The tunneling rate depends exponentially upon the correlation volume, hindering the observation of tunneling phenomena. In contrast, in a 2D vortex system, correlations are destroyed at high current densities; moreover, the correlation volume is very small due to the single cell limitation of vortex length in the crystalline c direction. This makes two-dimensional vortex systems adequate candidates for the observation of tunnel dissipation.

In a very different scenario, Fisher, Tokuyasu, and Young[14] have predicted a quantum variable-range hopping (VRH) dissipation in a two-dimensional superconductor at low temperatures but in the *linear* regime. Using classical arguments it has been shown that the vortex glass is not stable in two dimensions, i.e., the VG only exists at $T=0$ K.[15] Although, strictly speaking, the 2D vortex system is in the liquid state for any nonzero temperature, vortex glass correlations develop with a characteristic length scale ξ_{2D} which diverges at $T=0$ K as[15]

$$\xi_{2D}=a_0(\varepsilon_0 d/k_BT)^{\nu_{2D}},\tag{1}$$

where ν_{2D} is the 2D VG exponent, $a_0=(\phi_0/B)^{1/2}$ the intervortex spacing, and $\varepsilon_0 d$ the core energy of vortex segment of length d. At small current densities the length scales probed will be longer than ξ_{2D}. This causes, for nonzero temperatures, the activated motion of bundles of lateral size ξ_{2D} to move collectively. In the classical 2D VG theory, vortex motion involves thermal activation over barriers comparable to k_BT, leading to a linear (ohmic) resistivity term of the form[15]

$$\rho_{lin}\propto\exp[-(T_0/T)^p],\tag{2}$$

where T_0 is a characteristic temperature and the exponent p is equal or slightly larger than 1. When temperature is lowered, thermal activation has been proposed to crossover into the quantum variable range hopping (VRH).[14] VRH is due to vortex tunneling and also displays a linear resistivity as described by Eq. (2), but with the exponent p in the range 2/3–4/5. As $T\rightarrow0$ vortex motion ceases and the system freezes into a superconducting glass state, and a saturation of the resistance characteristic of tunneling is not observed. The relevant length scale, now, is the vortex localization length, a_v, which diverges when the superconductor insulator transition is approached by increasing external magnetic field.[14] Quantum VRH will dominate when a_v becomes comparable to the intervortex spacing.

In this paper we present experimental evidence for tunnel dissipation in oxygen depleted epitaxial $YBa_2Cu_3O_{6.4}$ thin films, for which we have recently established the 2D

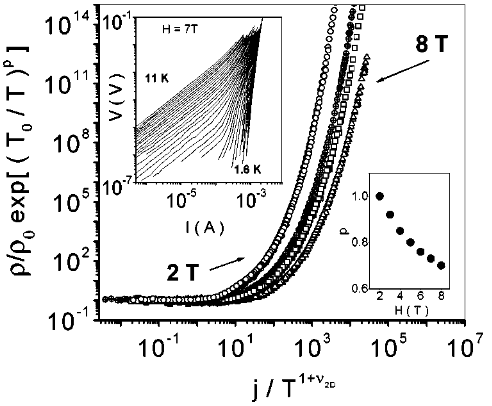

FIG. 1. $\rho - j$ scaling curves according to 2D VG theory with $T_g = 0$ K normalized at ρ_0, for $H = 2$, 4, 5, and 8 T with fixed parameters $\nu_{2D} = 2$, p and T_0 are those obtained from the fits of the $\rho_{lin}(T)$ data according to expression (2). The lower inset shows the magnetic field dependence of the exponent p. Upper inset: I-V characteristics in double logarithmic scale for $H = 7$ T. The temperature ranges from 1.6 (lower right) to 11 K(upper left) in increments of 0.2 K.

character.[16] We distinguish between two different mechanisms involving vortex tunneling: VRH, which occurs in the linear regime (at low current densities) and quantum creep in the nonlinear regime (high current densities). Linear resistivity data are used to show that increasing magnetic field above 2 T, the mechanism of dissipation at low temperatures, crosses over from thermal activation into quantum VRH. At high current densities, when temperature is reduced, the nonlinear resistivity becomes temperature independent, strongly suggesting quantum creep dissipation. Magnetic relaxation measurements have been performed to confirm this point.

High-quality epitaxial $YBa_2Cu_3O_{6.4}$ (YBCO) films were grown on (100) $SrTiO_3$ using a high-pressure (3.6 mbar pure oxygen) sputtering system. Substrate temperature was 900 °C, and oxygen content was adjusted *in situ* slowly following a stability line of the pressure-temperature-phase diagram[17] during sample cool down. Film thickness was kept in the range 500 to 700 A to ensure a homogeneous oxygen distribution. I-V curves were measured on photolithographically patterned bridges with dimensions 30×500 μm^2. Contacts were done on evaporated silver pads to ensure small contact resistances. Magnetic fields up to 8 T were applied parallel to c axis, and a temperature stability better than 50 mK was ensured prior to data acquisition.

In a previous paper[16] we have reported the pure two-dimensional character[18] of strongly oxygen depleted $YBa_2Cu_3O_{6.4}$ thin films in high magnetic fields (7 and 8 T) applied parallel to c axis. In this work we examine the behavior of the vortex system in magnetic fields higher than 2 T, for which a pure 2D vortex glass transition is observed. We have found the linear resistivity to follow the behavior of Eq. (2), leading to paramaters $T_0 = 230$ K for all fields and to a field-dependent p parameter varying between $p = 1 \pm 0.03$ at 2 T to 0.70 ± 0.03 at 8 T. The upper inset of Fig. 1 displays the nonlinear I-V characteristics on a double logarithmic scale for $YBa_2Cu_3O_{6.4}$ thin film measured in magnetic field of 7 T. Temperature ranges between 1.6 K at the lower right to 11 K at the upper left in increments of 0.2 K. The validity of the pure 2D vortex-glass model in our samples[16,17] is supported by critical scaling of $\rho - j$ curves according the pure 2D glass transition theory:[19] the same parameters p and T_0 extracted from the analysis of the resistance curves were used to construct plots of $\rho \exp[(T_0/T)^p]$ versus $j/T^{1+\nu_{2D}}$, where ρ is the linear resistivity and j is the measuring current. All isotherms collapse into a single master curve for each magnetic field. Figure 1 displays the scalings with $\nu_{2D} = 2$, and the parameters p and T_0 extracted from the linear resistivity ρ_{lin} described above. The linear resistivity has been normalized to show several scalings on the same plot. The excellent scalings of Fig. 1 provide evidence for a pure 2D vortex system with a magnetic-field dependent exponent p. Scalings were very sensitive to p, and departures beyond ± 0.03 in its value deteriorated them considerably. The interesting finding is that, when increasing magnetic field, the pure 2D vortex system crosses over from thermal activation ($p = 1$ at 2 T) into VRH (p varies in the range 4/5–2/3 for H in the range 5–8 T) (see lower inset of Fig. 1). This behavior can be understood as arising from the competition between classical and quantum dissipation, reflected in the relative values of the intervortex spacing a_0 and the vortex localization length a_v. Increasing magnetic field reduces a_0 and causes the superconducting transition to occur at lower temperatures. Low temperatures will reduce thermally activated vortex motion, and smaller a_0 values will favor tunneling when a_0 becomes comparable to the vortex localization length a_v.

The concept of variable range hopping was introduced to describe the transport of charge carriers through localized impurity states in doped semiconductors.[20] The basic idea is the competition between two processes involving tunneling: a) tunneling to an equal energy final state at a distance r_1, and b) the activation to a state with an energy difference δE followed by tunneling to a closer state at $r_2 < r_1$. Considering the $1/r^{\sigma}$ interaction between charges in a Coulomb gas, the hopping probability is optimized for a distance r_{opt} and yields the Mott conductivity law $\sigma \propto \exp[-(T_0/T)^p]$. VRH in a two-dimensional superconductor is an extension of these concepts to the vortex system. It is well known that disorder (pinning) destroys the long-range order of the Abrikosov lattice.[21] Localized vortices in a disordered energy landscape configure the scenario for the VRH dissipation. There will be a competition between the states located between $k_B T$ of the ground state and the states which are close enough to tunnel into. At low current densities, large hops will be probed which enhance vortex in plane correlations. This will cause that multivortex excitations, involving small rearrangements of many vortices [with an energy cost depending on distance as $1/r^{\nu_{2D}}$ (Ref. 14)] are energetically more favorable than single particle hops (with an energy cost depending logarithmically on distance in a 2D superconductor). The minimal energy multivortex excitations thus involve an energy scale U, which decreases with distance as an inverse power (in close analogy with the $1/r^{\sigma}$ interaction between charges in the Coulomb gas). The creation of a vortex excitation will involve many vortex tunneling events at a rate $\exp(-a_0/a_v)$

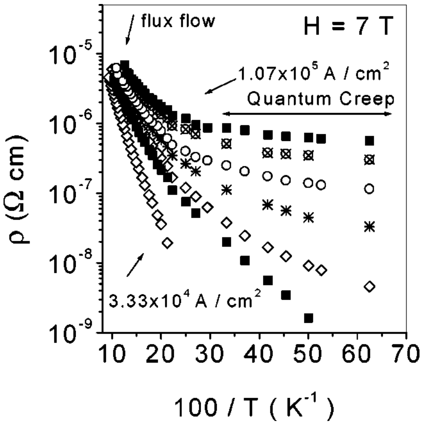

FIG. 2. Resistivity data ρ in magnetic field of 7 T, plotted vs $100/T$ for current densities of 3.33×10^4, 6×10^4, 6.66×10^4, 8×10^4, 9×10^4, 10^5, and 1.07×10^5 A/cm^2.

each. Thermal activation will reduce the probability by a factor $\exp(-U/T)$ but allows tunneling to a closer state. This determines an optimal distance and yields the Mott-like resistivity of the form $\varrho\propto\exp[-(T_0/T)^p]$, with the hopping exponent p in the range 2/3–4/5. It is important to stress that VRH is a mechanism occuring in the linear regime, at low currents, at which large hops are being probed thus favoring $1/r^{\nu_{2D}}$ multivortex interactions. VRH leads to a vanishing linear resistivity in the zero-temperature limit where a true superconducting glass state exists. Consequently, the saturation of the resistance, which is often considered as the characteristic signature of a tunneling process in a transport measurement, is not observed in the VRH mechanism.

At high currents, in the nonlinear regime, small distance hops are probed, thus reducing intervortex correlations. The reduction of the size of the tunneling object (correlation volume) increases the tunneling probability, and, as shown below, the saturation of the resistance is observed at low temperatures (quantum creep). Shown in Fig. 2 is the temperature dependence of the nonlinear resistivity in a magnetic field of 7 T and at high current densities ranging between 3.33×10^4 A/cm^2 and 10^5 A/cm^2. At temperatures $T<5$ K, the resistivity becomes temperature independent at high current densities strongly suggesting quantum creep dissipation.

In order to confirm that the temperature-independent dissipation at high currents is due to quantum creep, we have performed magnetic relaxation measurements using a SQUID magnetometer. The sample was cooled in zero field, and then a field $H=5$ T was applied in the c direction. Upon removal of the field, the irreversible magnetization was monitored for 14 h (5×10^4 s). Figure 3 shows the decay of the irreversible magnetization for several temperatures. The relaxation curves were fitted to expressions of the form $M_{irr}=a-b\ln(t/t_0)$, were t_0 is an arbitrary unit of time. Following the analysis by Stein *et al.*,[10] a decay time τ_D for which $M_{irr}\ (\tau_D)=0$, was estimated as $\tau_D=t_0\exp(a/b)$ which is independent of t_0. τ_D values obtained in this way are plotted in the inset of Fig. 3. A clear suppression of the temperature dependence of the dissipation can be noticed for temperatures lower than 5 K, confirming quantum creep.

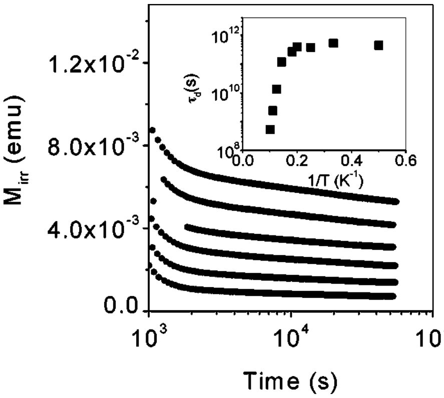

FIG. 3. Time dependence of the irreversible magnetic relaxation M$_{irr}$ measured at different temperatures (10 K, 9 K, 8 K, 5.5 K, 4 K, and 2 K, from bottom to the top), after removal of a magnetic field of 5 T. The inset shows the decay time τ_D versus $1/T$.

Quantum creep has been proposed previously to explain the supression of the activation energy of the magnetization relaxation rate in the highly anysotropic 2D superconductors $Bi_2Sr_2CaCu_2O_8$ (Ref. 22) and $Tl_2Ba_2CaCu_2O_8$,[23] and also in deoxygenated YBCO samples.[3] The extrapolated relaxation rate $Q(0)$ calculated as $-d\ln M_{irr}/d\ln t$ took values of 0.065. It can be interpreted in terms of the classical expression $Q(0)=(e^2/\hbar)\ \rho_n(0)/L(0)$, relating the rate to the 0 K normal state resistivity $\rho_n(0)$, and to the vortex segment length $L(0)$, yielding unexpectedly high values of $L(0)=14.9$ nm, for a 2D superconductor. This is in agreement with a very recently published analysis[4] implying that the former expression does not apply for pancake tunneling, and that dissipation takes place actually on a much larger length scale (L_{eff}) in the c direction. An estimate of the effective length scale as $L_{eff}=4/\pi^2(e^2/\hbar)\rho_n(0)/Q(0)$, according to the analysis by Hoekstra *et al.*,[4] yielded values of 6 nm well in the range obtained[4] for deoxygenated YBCO and highly anisotropic YBCO/PBCO superlattices. The quantum relaxation rate was also used to get an estimate of the action $S_E/\hbar$, and a value of 15.38 was obtained, in the same range of the values reported for $Y_{1-x}Pr_xBa_2Cu_3O_7$ by Stein *et al.*[10] It is important to remark that although magnetic relaxation measurements are used to support the quantum creep picture, observed at high current densities with transport measurements, this does not imply that the current densities induced in the relaxation experiment are large compared to the transport experiments. One has to be aware that although our pure 2D system has a zero-temperature glass transition, there is a wide critical region in which glass correlations exist. The magnetization experiment probes the glassy behavior, meanwhile, a transport experiment only probes glassy response at high current densities in a 2D superconductor.

In summary, we have shown direct evidence for quantum variable range vortex hopping in deoxygenated $YBa_2Cu_3O_{6.4}$ thin films at high fields and low current densities. This evidence is obtained from the temperature dependence of the linear resistivity, according to the pure 2D vortex glass transition theory. It is important to remark that the reason why VRH has not been observed previously is connected to the two basic requirements for this mechanism: VRH is a *low-*

temperature dissipation mechanism in a *pure 2D* system. Although 2D vortex system is found in the highly anisotropic TBCCO superconductor,[24] critical temperature is so high that very high magnetic fields would be necessary to reach the low-temperature tunnel dissipation regime. Deoxygenated YBCO with $x=6.4$, on the other hand, has a zero-field critical temperature of 25 K, so that magnetic fields in excess of 2 T are high enough to reach the low-temperature dissipation regime. When current density is increased at low temperatures ($T<5$ K), quantum creep dissipation (with a finite and constant value of the nonlinear resistivity) appears as a result of the reduced vortex correlations.

Z.S. gratefully acknowledges financial support from Agencia Española de Cooperación Internacional (AECI). Financial support from CICYT Grant Nos. MAT94-0604, MAT97-0675, and MAT99-1706E is also acknowledged. F.M. and R.E. acknowledge financial support from DGSCA-UNAM and CONACyT- MEXICO.

---

*On leave from Universidad del Quindio, Armenia, Colombia.

†Present address: Depto. de Fisica Aplicada, Universidad Carlos III de Madrid, 28911 Leganes, Spain.

[1] A.O. Caldeira and A.J. Leggett, Phys. Rev. Lett. **46**, 211 (1981).

[2] A.C. Mota, A. Pollini, P. Visani, K.A. Müller, and J.G. Bednorz, Phys. Rev. B **36**, 4011 (1987).

[3] A.J.J. van Dalen, R. Griessen, S. Libbrecht, Y. Bruynseraede, and E. Osquiguil, Phys. Rev. B **54**, 1366 (1996).

[4] A.F.Th Hoekstra, R. Griessen, A.M. Testa, J. el Fattahi, M. Brinkmann, K. Westerholt, W.K. Kwok, and G.W. Crabtree, Phys. Rev. Lett. **80**, 4293 (1998).

[5] L.Y. Glazman and N.Ya. Fogel, Fiz. Nizk. Temp. **10**, 95 (1984) [Sov. J. Low Temp. Phys. **10**, 51 (1984)].

[6] Y. Liu, D.B. Haviland, L.I. Glazman, and A.M. Goldman, Phys. Rev. Lett. **68**, 2224 (1992).

[7] D. Ephron, A. Yazdani, A. Kapitulnik, and M.R. Beasley, Phys. Rev. Lett. **76**, 1529 (1996).

[8] J.A. Chervenak and J.M. Valles, Jr., Phys. Rev. B **54**, R15 649 (1996).

[9] By linear regime it is understood that the average ratio of electric field (E) to current density (J) is identical to its differential value, i.e., the resistivity ρ is: $\rho=E/J=dE/dJ$.

[10] T. Stein, G.A. Levin, C.C. Almasan, D.A. Gajewski, and M.B. Maple, Phys. Rev. Lett. **82**, 2955 (1999).

[11] G. Blatter, V.B. Geshkenbein, and V.M. Vinokur, Phys. Rev. Lett. **66**, 3297 (1991).

[12] M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Phys. Rev. Lett. **63**, 2303 (1989).

[13] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994), Section II.A.5, Eqs. 2.103 and 2.106.

[14] M.P.A. Fisher, T.A. Tokuyasu, and A.P. Young, Phys. Rev. Lett. **66**, 2931 (1991).

[15] D.S. Fisher, M.P.A. Fisher, and D.A. Huse, Phys. Rev. B **43**, 130 (1991).

[16] Z. Sefrioui, D. Arias, M. Varela, M.A. López de la Torre, C. León, G. Loos, and J. Santamaria, Europhys. Lett. **48**, 679 (1999).

[17] Z. Sefrioui, D. Arias, M. Varela, J.E. Villegas, M.A. López de la Torre, C. León, G. Loos, and J. Santamaria, Phys. Rev. B **60**, 15 423 (1999).

[18] The term pure 2D refers to a system in which the vortex correlation length in the c direction is comparable to the CuO_2 planes separation, as opposed to quasi-2D systems, in which this length is smaller than sample thickness but larger than interplane distance. See Ref. 17.

[19] C. Dekker, P.J.M. Wöltgens, R.H. Koch, B.W. Hussey, and A. Gupta, Phys. Rev. Lett. **69**, 2717 (1992).

[20] B.I. Shklovskii and A.L. Efros, *Electronic Properties of Doped Semiconductors* (Springer, Berlin, 1984).

[21] A.I. Larkin and Yu.N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).

[22] D. Prost, L. Fruchter, I.A. Campbell, N. Motohira, and M. Konczykowski, Phys. Rev. B **47**, R3457 (1993).

[23] J. Tejada, E.M. Chudnovsky, and A. Garcia, Phys. Rev. B **47**, 11 552 (1993).

[24] H.H. Wen, H.A. Radovan, F.M. Kamm, P. Ziemann, S.L. Yan, L. Fang, and M.S. Si, Phys. Rev. Lett. **80**, 3859 (1998).