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Quantum tunneling of vortices in the $Tl_2CaBa_2Cu_2O_8$ superconductor

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Magnetic-relaxation measurements of a Tl-based high-T_c superconductor show temperature-independent flux creep below 6 K. The effect is analyzed in terms of the overdamped quantum diffusion of two-dimensional vortices. Good agreement between theory and experiment is found.

There is now a considerable experimental[1-3] and theoretical[4,5] interest in the quantum behavior of vortices in superconductors. According to the classical model of thermally activated flux creep in type-II superconductors,[6,7] the relaxation of the magnetic moment, due to the superconducting current, in the critical state, satisfies

$$M(t)=M(t_0)[1-S(T)\ln(t/t_0)] , \qquad (1)$$

where $S(T)=k_BT/U$ is the so-called magnetic viscosity and U is the average height of the energy barrier associated with the pinning of vortices. The underlying physical picture is quite simple.[6] After one switches off the external magnetic field, the Lorentz force $\mathbf{f}=(1/c)\mathbf{j}\times\mathbf{F}_0(F_0=ch/2e$ being the flux quantum) between the superconducting current, $\mathbf{j}=(1/c)\nabla\times\mathbf{M}$, and the vortices drives them out of the sample. This fast stage of the relaxation gets stuck in the critical state,[8] where f is balanced by the pinning force. Energy barriers just start to develop in this state. The following slow stage to the relaxation is due to the thermal activation of vortices out of potential wells. As j continues to drop, f becomes less than the pinning force, and the barriers grow such that at any observation time t metastable states having the lifetime $\tau\sim t$ contribute to the relaxation process. A simple calculation,[6] also known in the theory of disordered ferromagnets,[9,10] then shows that such a situation always leads to the ln(t) relaxation law.

The coefficient $S(T)=k_BT/U$ in front of the ln(t) originates from the relaxation time $\tau\propto\exp[U(1-j/j_c)/k_BT]$ for thermally activated processes. If quantum underbarrier depinning of vortices is

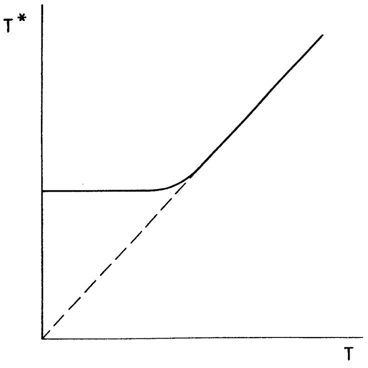

FIG. 1. Dependence $T^*(T)$.

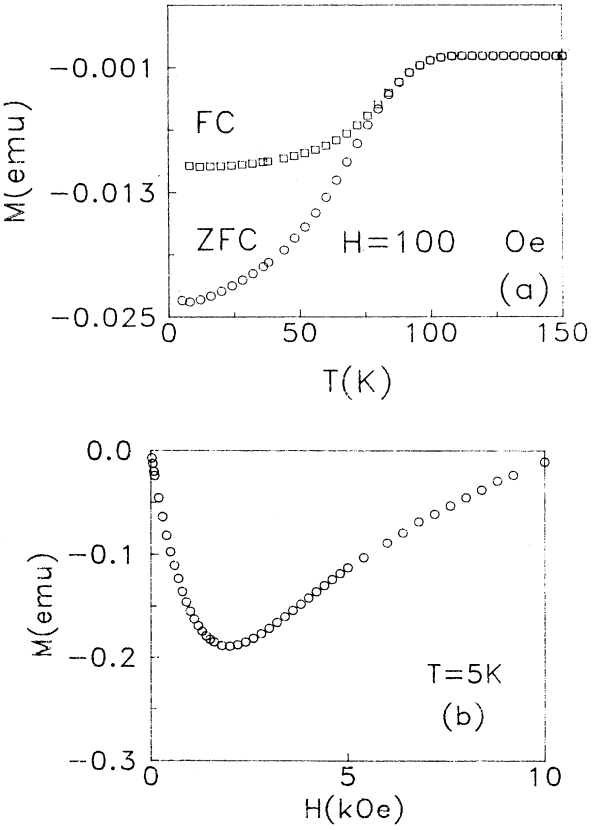

FIG. 2. (a) zfc and fc magnetization measurements in an applied field of $H=100$ Oe. (b) The M vs H curve at 5 K.

involved, T in this relation must be replaced by $T^*(T)$, which has the form[11] shown in Fig. 1. Correspondingly,

$$S(T)=k_B T^*(T)/U \ . \qquad (2)$$

A nonzero value of $S(0)$ would correspond to quantum diffusion of vortices in the pinning potential. Such a behavior of the magnetic viscosity has indeed been observed in $Pb_{1.2}Mo_{6.4}S_8$,[1] $YBa_2Cu_3O_{7-\delta}$,[2,3,12–14] and $Bi_2Sr_2CaCu_2O_{8+\delta}$.[2]

Theoretical attempts have been made to explain these observations in terms of collective quantum tunneling of vortex bundles.[4,5]

Our choice of the Tl-based high-T_c compound is dictated by the fact that it is an extreme case of anisotropic superconductor,[15] $m_c/m_{ab} \sim 10^4$. A flux line in such a superconductor is formed by a pancake structure of two-dimensional current rings in consequent CuO_2 layers. The rings belonging to different layers are weakly coupled by Josephson and electromagnetic interactions. Theoretical estimates show that the displacement of 2d vortices in the pancake with respect to each other up to a Josephson length[15,16] $\lambda_J=(m_c/m_{ab})^{1/2}d$ (where d is the interlayer distance) costs almost no energy. In the Tl superconductor, $\lambda_J \sim 10^3$ Å. The scale of the random pinning potential coincides with the radius of the vortex core, $\xi \sim 15$ Å. One should expect, therefore, that quantum (as well as thermal) flux creep in the Tl superconductor proceeds via single events involving individual 2d vortices, that is, relatively small objects. Correspondingly, quantum phenomena in this material should manifest themselves stronger than in other superconductors.

A powdered sample was prepared starting from suitable amounts of Tl_2O_3, CaO, BaO_2, and CuO, following the procedure described in Ref. [17]. X-ray-diffraction data and low-field (applied field 100 Oe) magnetization measurements [Fig. 2(a)] revealed that the sample consists of the phase $Tl_2Ba_2Ca_1Cu_2O_8$ with two CuO_2 planes; the critical temperature (onset) $T_c \approx 108$ K. The M vs H curve at 5 K is also shown [Fig. 2(b)]. The time decay of the magnetization was studied down to 1.8 K $(0.017 < T/T_c < 0.11)$ following two procedures. In the first one, the sample was cooled down to the working temperature in zero field (zfc process) and then a field ($H=1.5$ kOe) was applied and kept constant during the measurements [Fig. 3(a)]. In the second, the sample was cooled down in a low field ($H=100$ Oe, fc process) and the measurements were carried out after switching it off [Fig. 3(b)]. The applied fields in the relaxation experiments are resolved better than 0.1 Oe and were generated by using a very stable external power supply in order to avoid the decay of the magnetic field (that point was checked out through measurements with a paramagnetic sample). The temperature stability in the low-temperature regime was better than 0.01 K. Typical time decays were recorded for 2×10^3 sec. After each run was

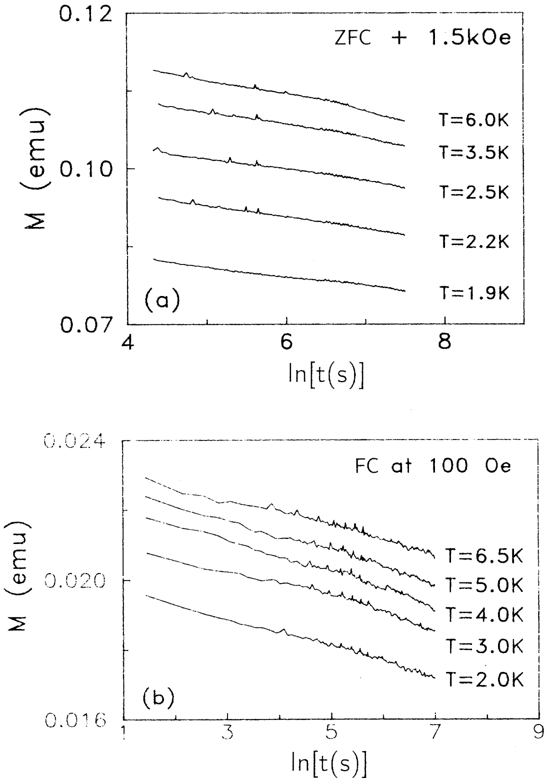

FIG. 3. Relaxation curves for (a) The zfc process with the application of a field ($H=1.5$ kOe) and (b) the fc process in a low field ($H=100$ Oe).

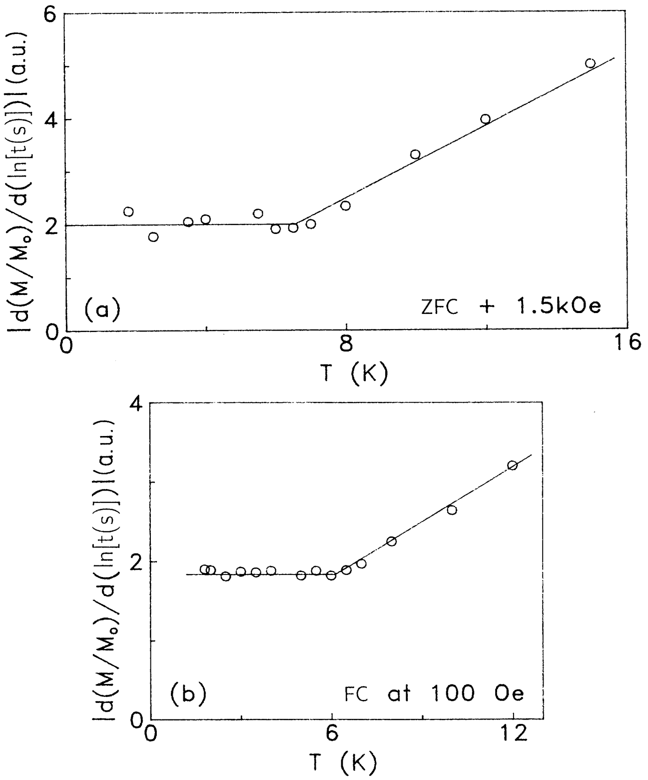

FIG. 4. Relaxation rates normalized to the first measured value of the magnetization for (a) zfc magnetization and (b) remanent magnetization. a.u. denotes arbitrary units.

completed, the sample temperature was raised well above T_c in order to remove completely the trapped flux lines. In both cases, purely logarithmic decays were observed in the whole temperature range investigated.

The relaxation rates normalized to the first measured value of the magnetization (M_0), $S=|(1/M_0)[dM/d\ln(t)]|$, are reported for the zero-field-cooled magnetization (S_{mzfc}) and for the remanent magnetization (S_{mr}) in Figs. 4(a) and 4(b), respectively. Both S_{mzfc} and S_{mr} decrease linearly with temperature down to 6.5 K, with a plateau for lower temperatures (i.e., down to 1.8 K); for comparison, such a plateau was observed in YBa-Cu-O single crystals[3] and powders,[18] but for $T<1$ K.

Let us now try to understand these results in terms of tunneling of 2*d* vortices. As has been already mentioned, pinning of the magnetic flux in the Tl superconductor occurs on a microscopic scale, $\xi\sim 15$ Å. For that reason, the relaxation in a powdered sample must be dominated by processes within grains. The tunneling rate is given by the WKB exponent, $\Gamma_Q\propto\exp(-B)$. As is known, the dynamics of vortices in type-II superconductors is entirely dissipative, the inertial mass of the vortex being in most cases irrelevant. For this case the Caldeira-Leggett theory[19] gives

$$B\sim\xi^2/\hbar\mu\ , \tag{3}$$

where μ is the mobility of the vortex. The theoretical result for a dirty superconductor is[20]

$$\mu=(\xi^2/\hbar)(\rho_n/\rho_0)\ , \tag{4}$$

where ρ_n is the normal sheet resistivity and $\rho_0=\pi\hbar/2e^2\approx 6.45$ kΩ is the quantum of the resistivity. Substituting Eq. (4) into Eq. (3) we obtain

$$B\sim\rho_0/\rho_n\ . \tag{5}$$

For the Tl superconductor[21] $\rho_n\sim 200$ Ω. This gives $B\sim 30$, a reasonable value to ensure the observable rate of tunneling.

Thermal activation processes are governed by the Boltzmann exponent, $\Gamma_T\propto\exp(-U/k_BT)$. Comparing Γ_T and Γ_Q, one finds that quantum processes dominate at $k_BT<k_BT_0\sim U/B$. Taking[22] $U\sim 150$ K, $B\sim 30$, we obtain $T_0\sim 5$ K in agreement with the observed crossover temperature.

In conclusion, we have observed the nonthermal flux creep in the Tl-based high-T_c superconductor. This observation is in agreement with the idea of quantum diffusion of two-dimensional vortices in $\mathrm{CuO_2}$ layers.

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