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Nonlinear Dynamics of Flux Creep in Underdoped Cuprates *

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We give a brief overview of transport and magnetic relaxation measurements in the mixed state of strongly underdoped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ crystals. Two phenomena are especially interesting from the point of view of both fundamental physics of "vortex matter" and power applications of high-T_c superconductors. First is the transition from thermally activated flux creep to temperature independent quantum flux creep which is observed in both transport and magnetic relaxation measurements at temperatures $T \leq 5\ K$. Flux transformer measurements indicate that the crossover to quantum creep is preceded by a coupling transition. Second, in the mixed state below the coupling transition, the dissipation is non-ohmic, and we speculate that, as a result, the current distribution may be unstable with respect to self-channeling, resulting in the formation of thin current-carrying layers.

1. Introduction

The dissipation of underdoped cuprates can be measured down to much lower reduced temperatures T/T_c than in optimally doped cuprates in relatively small fields of a few tesla due to their lower upper critical field. This allows the study of a broader range of the magnetic field - temperature $H-T$ phase diagram of "vortex matter" than in the optimally-doped superconductors.

Here we present an overview of the dynamics of flux creep in underdoped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with an emphasis on the phenomenon of quantum creep - temperature independent dissipation of the supercurrent - observed in both transport and magnetic relaxation measurements. Superconductors represent, perhaps, the only system in which relaxation of a macroscopic nonequilibrium state due to quantum creep of the flux vortices is an experimentally accessible phenomenon. In the majority of the other macroscopic metastable systems, relaxation proceeds as a sequence of a large number of uncorrelated microscopic steps, requiring thermal activation over an energy barrier.

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A second important aspect of the vortex matter behavior which transpires from our study is that the dissipation becomes non-ohmic below a certain temperature identified as the coupling transition temperature. We speculate that the non-ohmic dissipation may give rise to a highly nonuniform current distribution (much more so than in the normal state) through the formation of a very thin channel (self-channeling) that carries a current density close to its critical value, while the rest of the sample carries only a fraction of the total current. Understanding this phenomenon may have significant implications for power applications of layered superconductors.

2. Quantum Creep

Measurements were carried out on two strongly underdoped twinned single crystals of $Y_{0.47}Pr_{0.53}Ba_2Cu_3O_{7-\delta}$ with $T_c \approx 17$ and $21\ K$. The first sample was used for transport measurements with the "flux transformer" contact configuration [inset to Fig.1(a)]: the current I was injected through the contacts on one face of the sample (1,4) and the voltage drop between the voltage contacts on the same (primary voltage $V_{23} \equiv V_p$) and the opposite (secondary voltage $V_{67} \equiv V_s$) faces was measured for temperature, total current, and magnetic field

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H, applied parallel to the c-axis, in the ranges $1.9\ K \leq T \leq 25\ K$, $0.3\ \mu A \leq I \leq 2\ mA$, and $0.2\ T \leq H \leq 9\ T$. Magnetic relaxation measurements were performed on the second crystal using a $SQUID$ magnetometer. The crystal was cooled in zero field; a field $H + \Delta H$ ($\Delta H = 0.3\ T$ for all H) was applied parallel to its c-axis, and then the field was reduced to H. The decay of the resultant paramagnetic moment was monitored for several hours ($\approx 10^4\ s$) in constant H.

Figure 1(a) gives an overview of the dependence of V_p and V_s on T and H. Both voltages are normalized to I and H. Below 9 K, V_p and V_s exhibit activated behavior with field-dependent activation energies. At even lower T, the primary signal becomes T-independent and scales approximately with H, while the secondary voltage remains thermally activated.

Figure 2 is an expanded view of $V_{p,s}$ vs $1/T$ for $H = 1.5\ T$ and $I = 10\ \mu A$. The activation energies of both V_p and V_s (slopes of these curves) change suddenly at the coupling transition temperature $T^*(H)$. In addition, the dissipation becomes strongly non-ohmic below T^* (see details in [1,2]). As a result, the activation energies, which are equal and current-independent at $T > T^*$, become current-dependent at $T < T^*$. At low currents, the activation energy below T^* is *greater* than above T^* so that the curves $V_{p,s}(1/T)$ have a downward curvature (see Fig. 2). However, the activation energy decreases with increasing current and at sufficiently large currents it becomes smaller than it is at $T > T^*$, so that $V_p(1/T)$ acquires an upward curvature [1,2].

Magnetic relaxation measurements corroborate the assertion that the saturation of the primary voltage in Figs. 1(a) and 2 is due to quantum creep. Within the decade of time $10^3 - 10^4\ s$, the magnetic relaxation curves are well fitted to $M_{irr} = a - b\ln(t/t_0)$, where t_0 is an arbitrary unit of time. We define the decay time τ_d as the time over which the irreversible part of the magnetic moment M_{irr}, induced by the supercurrent, loses a substantial fraction of its initial value. Hence, we estimate the decay time by extrapolating the $M_{irr}(t)$ dependence to $M_{irr}(\tau_d) = 0$; this gives:

$$\tau_d = t_0 \exp\{a/b\}. \quad (1)$$

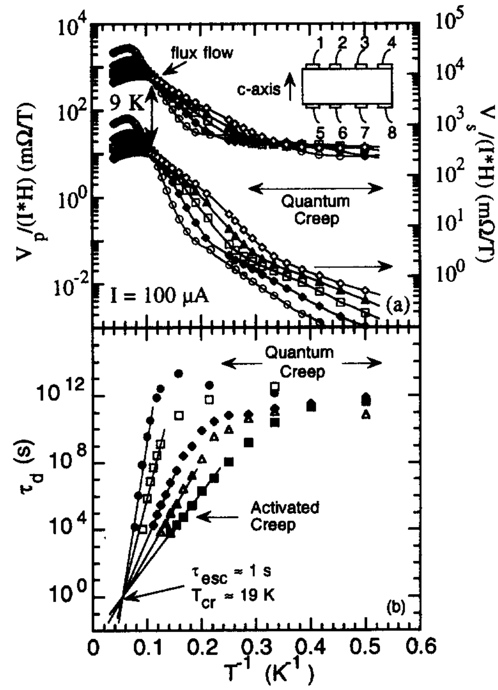

Figure 1. **(a)** Primary V_p and secondary V_s voltages, normalized to the total current I and magnetic field H, plotted vs T^{-1} for $H = 0.2, 0.4, 0.6, 0.8$ and $1\ T$. The slope decreases with increasing field. **Inset:** Contact configuration used in the measurements. **(b)** Decay time τ_d of magnetic moment (see definition in text) vs T^{-1} for several values of magnetic field ($H = 0.1$, 0.2, 0.6, 0.8, and 1.2 T). The slope decreases with increasing field. The straight line extrapolations of the Arrhenius-type dependence converge at $T_{cr} \approx 18 - 19\ K$ and $\tau_{esc} \approx 1 - 2\ s$. The saturation of τ_d at the level $10^{11} - 10^{12} s$ is due to quantum creep.

With this definition, τ_d is universal and does not depend on the choice of t_0. Figure 1(b) is a plot of τ_d, calculated according to Eq. (1), vs $1/T$ for different values of H. At high temperatures the data display an Arrhenius dependence with a slope decreasing with increasing H. This trend is consistent with the field dependence of the ac-

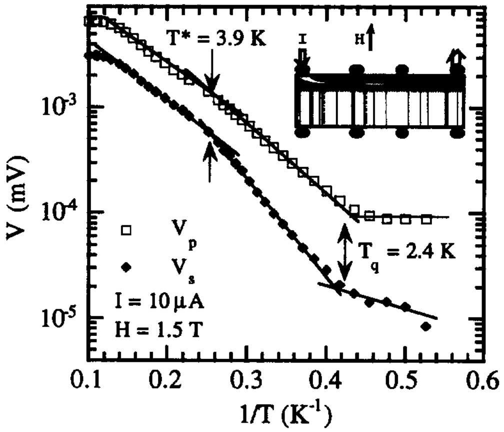

Figure 2. Arrhenius plots of the primary V_p and secondary V_s voltages measured $H = 1.5\ T$ and $I = 10\ \mu A$. **Inset** : Schematic representation of the current distribution. The current flows mainly in the upper (shaded) layer. The vortices are coupled within each layer, but the layers are decoupled from each other.

tivation energy in transport measurements [Fig. 1(a)]. The T-dependence of the decay time in the activated regime is given by [2]:

$$\tau_d = \tau_{esc} \exp\left\{U(H)\left(\frac{1}{T} - \frac{1}{T_{cr}}\right)\right\}, \qquad (2)$$

where the *escape* time $\tau_{esc} \approx 1s$ and $T_{cr} \approx 19\ K$ are obtain from fitting the data in the activated regime.

Below a certain temperature $T_q(H)$, the decay time saturates at a roughly T- and H-independent level [Fig. 1(b)]. The values of $T_q(H)$ from transport [Fig. 1(a)] and magnetic relaxation [Fig. 1(b)] measurements are very close in spite of a very large difference in the currents involved in these measurements. The fact that the transition to a temperature independent dissipation takes place in both transport and magnetic relaxation processes and at approximately the same temperature in a given field indicates that both phenomena have the same origin, namely, reflect the quantum creep of the flux vortices.

Currently, quantum creep has been treated theoretically as a tunneling of a single vortex through a potential barrier, see Refs. [1–3] and references therein. However, numerous studies of classical motion of periodic media, such as vortex lattice, under the action of a driving force in the presence of static disorder indicate a far more complex behavior than random uncorrelated diffusion of individual elements. For example, the vortex lattice appears to flow along well-defined channels in the pinning potential [4]. For this reason, non-activated transport and relaxation could also involve a large number of vortices moving coherently along certain elastic channels and forming "quantum" avalanches triggered by non-activated rearrangements due to quantum transitions between different configurations of vortices. Such processes very likely would lead to a much greater relaxation rate than that estimated from the single vortex tunneling model. The fact that the underdoped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals exhibit quantum creep at relatively high temperatures, makes them good candidates for future studies of this unique phenomenon in order to elucidate the details of quantum relaxation of nonequilibrium metastable states.

3. Self-Channeling of the Transport Current

The fact that quantum creep manifests itself only in the primary voltage, while the secondary voltage remains thermally activated [Fig. 1(a) and Fig. 2] points towards the model of current distribution shown in the inset to Fig. 2. The transport current is mostly confined within a narrow layer below the current contacts. The rest of the sample remains relatively undisturbed. These two regions of the sample are uncoupled and, inside each of them, the vortices are coherent over a distance comparable to the thickness of the respective layer. Temperature independent V_p indicates that the thickness of the current-carrying layer is just a few unit cells (which makes it similar to ultra thin films and multilayers, the only other systems in which quantum creep was observed in transport measurements). The small length of vortices and high density of current would make tunneling a dominant mechanism even at relatively high temperatures ($T \approx 5$ K); the vortices in the lower layer do not tunnel because of the much longer correlation length and, hence, V_s remains thermally activated.

These findings open the question of the nature of such a drastic self-channeling of the transport current. We have argued that the coupling transition and accompanied non-ohmic dissipation may lead to the instability of the current distribution with respect to the formation of a thin current-carrying layer [1,2]. The thickness of this layer D_{eff} is determined by the condition that the density of current does not exceed the critical current density j_c; i.e., $D_{eff} \geq I/j_c$. When the transport current I is small, as is the case in our experiments, it can compress itself into a layer only a few unit cells thick. To avoid misunderstanding, we emphasize that these channels are entirely different from those discussed in Ref. [4]. The elastic channels along which the vortices slide are bounded by vertical (parallel to the field) sheets whose location is determined by the profile of the pinning potential. In contrast, the current-carrying layer is parallel to the CuO_2 planes and its formation is due to a dynamic instability inherent probably only to layered superconductors with weak coupling between the layers.

In our contact configuration (insets to Figs. 1 and 2), the current-carrying layer is necessarily pinned to the surface where the current contacts are located. Whether this is always the case, even when the boundary conditions do not favor its formation near the surface, is an open question. One could argue that when the current-carrying layer is formed at the surface of the sample there is only one boundary with the phase slip, which is more favorable then having two such boundaries if the layer is formed inside the sample.

There is additional evidence corroborating the scenario of self-channeling. It is known that the critical current density in thin films of high-T_c superconductors is substantially higher than in single crystals. The critical current is defined as the current at which the potential drop between voltage contacts attached to the surface of the sample exceeds a certain threshold value. The critical current density is calculated assuming that the current fills uniformly the cross section of the sample. However, if there is instability of the current distribution, as we suggest, these measurements on single crystals determine the threshold of instability leading to the formation of the current-carrying layer pinned to the surface, rather than the critical current density as in thin films.

Another corroborating evidence of self channeling comes from our magnetic relaxation experiments devised to reduce the giant flux creep in the critical state [5]. This was accomplished by raising the temperature of the sample for a short time (by heat pulses), thus, creating a *supercritical* state which decays rapidly so that, when the temperature returns to its operating level, the sample is in a subcritical state with a smaller dissipation. Unexpectedly, we found that, although a relatively small increase of temperature above the operating temperature for a short period of time leads to a noticeable decrease of the relaxation rate, greater increases in temperature do not lead to a further decrease of the relaxation rate. This can be understood as a result of the instability of the uniform distribution of the shielding current along c-axis. This would lead to the formation, at the surfaces of the sample, of current-carrying layers with much greater than average current density. The rate of dissipation in such layers would remain constant at a given temperature, even though the *total current* flowing through the sample becomes smaller and smaller as a result of heat pulses with increasing amplitudes.

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