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Experimental evidence of quantum tunnelling in TlBaCaCuO

A Garcia†, X X Zhang†, A M Testa‡, D Fiorani‡ and J Tejada†

† Departament de Fisica Fonamental, Facultat de Física, Universitat de Barcelona, Barcelona, Spain

‡ ITSE, Area della Ricerca di Roma, Rome, Italy

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Abstract. Experimental evidence of a crossover from a thermally to a non-thermally activated flux motion is reported for TlBaCaCuO. It was obtained by measuring the time decay of both zero-field-cooled and remanent magnetization. The measured relaxation rates at low temperature are in good agreement with the prediction of the quantum collective creep theory for anisotropic superconductors in the low-field–single-vortex pinning.

1. Introduction

Physical systems having states separated from the neighbouring states by high potential barriers are known to exhibit decays via thermal activation and quantum mechanical tunnelling. In particular, the study of metastable states in a variety of physical systems (Josephson junctions [1], charge density waves [2], metastable vacuum [3] and magnetic systems; e.g. magnetic grains [4], ferrofluids [5] and magnetic multilayers [6]) has revealed that at sufficiently low temperatures thermal activation is changed to quantum tunnelling.

Recently, the possibility of quantum tunnelling for a system of magnetic vortices has been investigated both in high- [7–11] and in low-temperature superconductors [12–14] where, in contrast to the standard model of thermally activated flux motion [15] (which predicts at low temperatures a vanishing magnetic relaxation rate), the relaxation rate has been found not to extrapolate to zero.

In this work we report the results of low-temperature ($T/T_c \ll 1$) magnetic relaxation measurements performed on bulk samples (powders) of $Tl_2Ba_2Ca_1Cu_2O_{8-x}$, with evidence of a crossover from thermally to non-thermally activated flux motion.

2. Results and discussion

A powdered sample was prepared starting from suitable amounts of Tl_2O_3, CaO, BaO_2 and CuO, following the procedure described in [16]. X-ray diffraction data and low-field (applied field $H_a = 5$ Oe) magnetization measurements, carried out with a commercial SQUID magnetometer (figure 1), revealed that the sample consists

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of the phase with two CuO_2 planes ($Tl_2Ba_2Ca_1Cu_2O_8$), with a critical temperature (onset) $T_{c0} \simeq 108$ K. 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, the sample was cooled down to the working temperature in zero field and then a field ($H = 1.5$ kOe) was applied and kept constant during the measurements (figure 2(*a*)). In the second, the sample was cooled down in a low field ($H = 0.1$ kOe) and the measurements were carried out after switching it off (figure 2(*b*)). Typical time decays were recorded for 2×10^3 s. After each run was completed, the sample temperature was raised well above T_c in order to remove completely the trapped flux lines. In both cases logarithmic decays were observed in the whole temperature range investigated, apart from small deviations at short times. Moreover, the value and the temperature behaviour of the relaxation rate seems to be not affected by the magnitude of the applied field and by the measuring procedure.

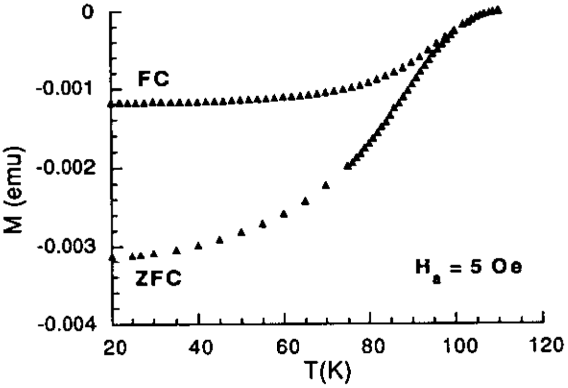

Figure 1. Zero-field-cooled and field-cooled magnetization as a function of temperature (applied field $H_a = 5$ Oe).

Figures 3(*a*) and 3(*b*) show the relaxation rates normalized to the first measured value of the magnetization (M_0), $R = [(1/M_0)(\mathrm{d}M/\mathrm{d}\ln t)]$, for the zero-field-cooled magnetization ($R_{M\mathrm{zfc}}$) and for the remanent magnetization ($R_{M\mathrm{r}}$) respectively. Both $R_{M\mathrm{zfc}}$ and $R_{M\mathrm{r}}$ decrease linearly with temperature down to 6.5 K, with a plateau extending down to 1.8 K.

The occurrence of a temperature independent logarithmic relaxation rate has been reported for a variety of YBCO samples at low temperatures ($T < 1$ K) [10, 11], as well as for $T > 20$ K (see [17] and references therein). While in the former case an explanation has been given in terms of quantum tunnelling, in the latter the data have been explained in the framework of the vortex glass model [18]. The model, predicting a linear temperature dependence of R with a crossover into a temperature independent plateau, ignores quantum tunnelling at low temperatures.

It has been shown [19] that in a purely 2D flux line lattice (FLL) the vortex glass phase is absent at any finite temperature, while in a quasi-2D FLL the glass phase can exist but with a transition temperature lower than the FLL melting temperature (for Bi and Tl compounds it is estimated to be within the range 20–40 K). Layered superconductors (i.e. Bi and Tl based materials), due to their large anisotropies

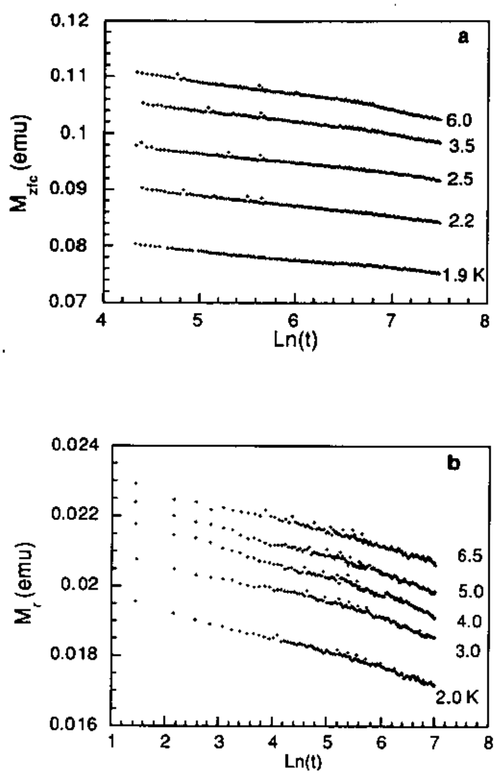

Figure 2. Time decay of the magnetization at different temperatures: (*a*) zero-field-cooled magnetization ($H_a = 1.5$ kOe); (*b*) remanent magnetization (field applied during the cooling $H_a = 0.1$ kOe).

(values of the anisotropy factor Γ are $\geqslant 3000$ [20] and $\geqslant 10^5$ [21] for Bi and Tl respectively), should be considered as a stacking of Josephson coupled sheets in which a 2D vortex lattice exists. Moreover, concerning the dimensionality of the FLL in YBCO and Tl systems, it should be noted that the effective Josephson length, $\Lambda = \Gamma^{1/2}d$ (d is the spacing between the Cu–O planes), is $\simeq 35$ Å and $\simeq 4700$ Å respectively. By virtue of this, we choose to analyse the experimental data following the theoretical treatment of Blatter *et al* [22], who have recently tackled the problem of quantum flux creep in bulk superconductors in the framework of the collective pinning theory.

The tunnelling rate T is determined by the effective Euclidean action S_E^{eff} (the action which takes into account the coupling of the tunnelling object to its environment [23]) of the process, $T \propto (-S_E^{eff}/\hbar)$. In the limit of weak fields and strong dissipation, large relaxation rates are predicted [22] for material characterized by a small coherence length and by a large normal state resistivity (ρ_n).

For anisotropic superconductors in the single-vortex regime (this should be the case for fields low enough, as long as the vortex length is lower than the mean distance between neighbouring vortices, $L_c < a_0$) the effective action is given by

$$S_E^{eff}/\hbar = \Gamma^{-1/2}(\hbar/e^2)(\xi/\rho_n)\sqrt{(J_0/J_c}$$

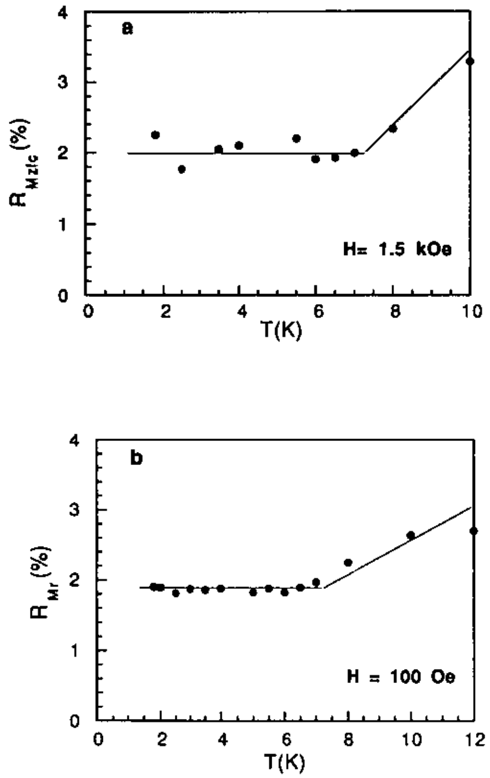

Figure 3. Normalized relaxation rate of the magnetization as a function of temperature: (*a*) zero-field-cooled magnetization ($H_a = 1.5$ kOe); (*b*) remanent magnetization (field applied during the cooling $H_a = 0.1$ kOe).

where ξ is the coherence length, ρ_n the normal state resistivity extrapolated to zero temperature and J_0/J_c the depairing–critical current density ratio.

However, as the collective pinning length $L_c \cong \xi(J_0/J_c)^{1/2}\Gamma^{-1/2}$ ($\simeq 1$ Å) is much smaller than the mean distance between neighbouring vortices $a_0 = 1.075(\phi_0/B)^{1/2}$ ($\simeq 1200$ Å at $H = 1.5$ kOe) and also smaller than the spacing (d) between the Cu–O planes ($\cong 15$ Å for the 2212 phase [24]) single pancakes of flux lines should be the actual tunnelling objects. In this case the effective action should be given by:

$$S_E^{eff}/\hbar = (\hbar/e^2)(d/\rho_n)$$

Taking $\rho_n = 10$–20 $\mu\Omega$cm [25], $J_0/J_c \simeq 200$ and $\xi \simeq 30$ Å, the calculated relaxation rate is $R = \hbar/S_E^{eff} \simeq 2$–$3\%$, consistent with the experimental $(1/M_0)\mathrm{d}M/\mathrm{d}\ln t$ value.

The result obtained by Blatter *et al* [22] for S_E^{eff} is strictly valid in the limit of $T \to 0$. In principle the quantum tunnelling can be thermally assisted, leading to an increase of the magnetic relaxation rate. The correction to the quantum tunnelling at finite temperatures has been calculated [11], predicting an increase of R as $A + BT^2$ below a crossover temperature $T_{qc} = \hbar/t_c k_B$, where t_c is the characteristic tunnelling time. Actually, no crossover is observed in our data as also reported for YBCO [11]; instead, the linear R versus T behaviour characteristic of the standard model of the thermally activated flux creep [15] is observed for $T > 6.5$ K.

The observed behaviour gives strong support to the quantum tunnelling hypothesis. A comparison of our results to those for YBCO reveals that the temperature range for the non-thermally activated flux motion is wider for the Tl compound, exhibiting a higher relaxation rate (2% to be compared to ~ 0.4% in $YBa_2Cu_4O_8$ powders [11] and ~ 0.7% in $YBa_2Cu_3O_7$ single crystals [26]). This is due to the quasi-2D character of the Tl-based material, where the distance between the CuO–2 planes is about 3–4 times the coherence length along the c axis. As a consequence, the tunnelling could be considered as a process involving 2D pancake vortices rather than 3D vortex lines [27–30].

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