Paramagnetic Meissner effect at high fields in YCaBaCuO single crystal

F T Dias¹, V. N. Vieira¹, A. L. Falck¹, D. L. da Silva¹, P Pureur² and J Schaf²

¹Instituto de Física e Matemática, Universidade Federal de Pelotas, RS, Brazil
²Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil

e-mail: fabio.dias@ufpel.edu.br (Fábio Dias)

Abstract. We report on systematic magnetization experiments in an Y₁₋ₓCaₓBa₂Cu₃O₇₋δ (x = 0.25 at%) single crystal. The magnetization experiments were made using a superconducting quantum interference device magnetometer (SQUID). Magnetic moments were measured as functions of the temperature according to the zero-field cooling (ZFC), field-cooled cooling (FCC), and field-cooled warming (FCW) prescriptions. The time-dependence of the FC magnetization at fixed magnetic fields was studied. Magnetic fields up to 50 kOe were applied and a paramagnetic response related to the superconducting state was observed when strong enough fields were applied parallel to the c axis. The magnitude of the high field paramagnetic moment (HFPME) increases when the field is augmented. The effect shows strong and anomalous time dependence, such that the paramagnetic moment increases as a function of the time. An YBa₂Cu₃O₇₋δ single crystal exhibiting the same effect was used for comparison. We discuss our results in terms of the flux compression scenario into the sample modulated by Ca concentration.

1. Introduction

The Meissner paramagnetic effect (PME) is characterized by a paramagnetic response of the field cooled (FC) magnetization when a superconductor sample is field cooled through its critical temperature, T_c [1-7]. In the literate [1-7], the PME is distinguished between: the low-field PME (LFPME) [1-4] and the high-field PME (HFPME) [5-7]. The LFPME usually has its paramagnetic response gradually increased when H ≤ 10 Oe are applied. On the other hand, when H > 10 Oe are applied the LFPME is rapidly suppressed and conventional Meissner magnetization response is observed. [1-4] There are successful theories explanations for the LFPME such as randomly oriented π junctions [8], flux compression [9] and the giant vortex state [10]. The HFPME shows some noticeable differences when compared to the LFPME. For instance, the magnitude of the HFPME moment increases when strong magnetic fields (H ≥ 1 kOe) are applied [5-7], its FC magnetization time-dependence is strong and anomalous. On the other hand, the theories approaches applied to the explanation of the LFPME are unsuccessful to explain the HFPME [5-7]. According to some authors [5-7] a detailed description of the relation between HFPME and pinning mechanisms still lacking since the existing flux-compressed scenarios do not take into consideration the crucial role of the pinning mechanism, nor the importance of vortex dynamics.
Motivated by the last considerations we report on field and time dependence of the FC magnetizations in a YBa$_2$Cu$_3$O$_{7-\delta}$ [YBaCuO] and a Y$_{1-x}$Ca$_x$Ba$_2$Cu$_3$O$_{7-\delta}$ (x = 0.0025) [(YCa)BaCuO] single crystals with the proposal of study the role of the chemically introduced pinning mechanisms on the HFPME behavior contrasting these results with a no doped sample.

2. Experimental techniques and method of analysis

The single crystal samples of the studied systems were grown by the self-flux method [11]. The crystals were analyzed by X-ray diffraction [11]. The polarized light microscopy specifies that our single crystals are heavily twinned [11].

DC magnetization measurements were performed with a Quantum Design MPMS-XL SQUID magnetometer in DC mode. The SQUID signal and the sample centering were visually monitored during the experimental run. Magnetic fields from 1 to 50 kOe were applied perpendicular to c axis of the single crystals. Magnetic moments were measured as function of the temperature according to the zero field cooling (ZFC), field cooled cooling (FCC), and field-cooled warming (FCW) protocols. The time dependence of the FCC moment at a fixed temperature was studied up to a time of the 50.000s. All results were corrected for the corresponding demagnetization effect and sample holder signal contributions.

3. Results and discussion

Figure 1 displays the temperature evolution of the FCC (closed symbols) and the FCW (open symbols) DC magnetizations for YBaCuO and (YCa)BaCuO single crystals as function of applied field.

![Figure 1. FCC and FCW magnetizations for our YBa$_2$Cu$_3$O$_{7-\delta}$ (left panel) and Y$_{1-x}$Ca$_x$Ba$_2$Cu$_3$O$_{7-\delta}$ (x = 0.0025) (right panel) samples to the H // c. Measurements were performed using a cooling and a warming rate of the 3 K/min.](image-url)
In both samples, for \( H < 1 \) kOe, not showed in figure 1, the LFPME is absent and FCC and FCW magnetizations decrease in the whole temperature range below \( T_c \) showing the usual Meissner behavior. However, when \( H \geq 1 \) kOe the FCC and FCW magnetizations exhibit a diamagnetic “dip” in the temperature, \( T_d \) that became more pronounced in YBaCuO sample as \( H \) is augmented. On the other hand, for \( T < T_d \) the FCC and FCW magnetic moments increase steadily as temperature is lowered and attain a positive value which essentially exceeds the magnetization values in the normal state when \( H \geq 10 \) kOe are applied. This behavior is the signature of the HFPME and was observed in \( YBa_2Cu_3O_{7-\delta} \) single crystals [6] and melted textured samples [7]. It is important to note that the FCC and FCW magnetizations for our samples show a weak irreversibility as well as the HFPME magnitude of the Ca doped sample shows no tendency to saturate as temperature decreases towards to zero and improves the magnitude of this effect as compared to the YBaCuO sample [6,7].

Figure 2 shows for both single crystals the FCC magnetization time-dependence as a function of the applied magnetic field. The magnetic moment time dependence was measured for approximately 50,000 s after field cooling the samples at 10 K/min from 100 K to 40 K. In the figure, \( M_0 \) represents the first measured value of the FCC magnetization time-dependence.

![Figure 2](image)

**Figure 2.** Time dependence of the FCC magnetization for our \( YBa_2Cu_3O_{7-\delta} \) (left panel) and \( Y_{1-x}Ca_xBa_2Cu_3O_{7-\delta} \) (\( x = 0.0025 \)) (right panel) samples to the \( H // c \). Measurements were performed at \( T = 40 \) K after a field cooling rate of the 10 K/min.

The behavior of the FCC moment time-dependence of the YBaCuO and the \( Y(Ca)BaCuO \) samples is very similar. While the applied magnetic field increases from 0.1 kOe to 50 kOe the FCC moment time-dependence monotonically proceeds from a diamagnetic to a paramagnetic performance. Remarkable in the results of Figure 2 is the fact that paramagnetic moments obtained after field cooling the samples relax monotonically to increasing positive values showing no time tendency to saturate.
The Ca doping acts as an efficient pinning centres in the microstructure YBa$_2$Cu$_3$O$_{7-\delta}$ [12,13]. Particularity, Ca substitutions give rise to formation of rows of oxygen vacancies with pronounced strain fields in the CuO$_2$ superconducting planes [12,13]. The defects thus formed seem to be analogous to array of normal nanodots in CuO$_2$ planes which are expected to have strong intragrain pinning interactions with vortices state structure.

HFPME results reported from Rykov [6] for an optimally doped and an overdoped YBaCuO single crystal display that the HFPME magnitude is suppressed in the overdoped sample. According to the authors, it is justified because HFPME magnitude is correlated to the structural disorder, like oxygen vacancies, that in the overdoped sample is smaller than optimally doped sample. The HFPME results showed in the Figure 1 are in agreement with this prediction once the HFPME magnitude is more intensity in Ca doped sample where the structural disorder character, enhanced by chemically substitution, is stronger than that one of the YBaCuO sample.

The behaviour of the FCC moment time-dependence, displayed in Figure 2, for our single crystals shows that as applied magnetic field is augmented more extra flux is allowed to penetrate the sample supporting an establishment of a flux compression scenario. A similar behaviour was observed in melted textured YBa$_2$Cu$_3$O$_{7-\delta}$ samples [7].

The weak irreversibility displayed by FCC and FCW magnetizations of our samples where stronger magnetic filed were applied as well as the enhancement of the HFPME by Ca doping suggest the establishment of a flux compressed state modulated by pinning as a probably responsible to the origin of the HFPME in our samples. In agreement with this scenario, we believe that in some regions of the samples, where pinning is strong, the vortex density can be depleted below that expected from equilibrium state. Consequently, this state opens a place for the admission of extra vortices into the sample, originating the HFPME.

Thus, it may be possible that pinning plays an important role to explain the HFPME in our samples. More studies are necessary in order to understand the correlated mechanism in both samples. The time dependence of FCC magnetization and the crucial role of the pinning mechanism in the YCaBaCuO single crystal are under current investigation.

Acknowledgments
The authors thank to the CNPq Universal Program, under contract N° (483100/2009-9), for partially financing this work.

References
[1] Svedlindh P, Niskanen K, Norling P, et al 1989 Physica C 4162-164 1365
[2] Riedling S, Brauchle G, Lucht R, et al 1994 Physical Review B 49 13283
[3] Sandim M J R, Stamopoulos D, Ghivelder L, et al 2010 J. Supercond. Nov. Magn. 23 1533
[4] Pradip Das, Tomy C V, Takeya H, et al 2009 J. of Physics: Conference Series 150 052041
[5] Prokhorov V G, Svetchnikov V L, Park J S, et al 2009 J. Supercond. Sci. Technol. 22 045027
[6] Rykov A I, Tajima S and Kusmartsev F V, 1997 Physical Review B 55 8557
[7] Dias F T, Pureur P, Rodrigues P, et al 2004 Physical Review B 70 224519
[8] Sigrist M and Rice T M, 1992 EJ. Phys. Soc. Jpn. 51 4283
[9] Koshelev A E and Larkin A I, 1995 Physical Review B 52 13559
[10] Moshchalkov V V, Qi X G and Bruyndonex V, 1997 Physical Review B 55 11793
[11] Vieira V N, Riegel I C and Schaf J, 2007 Physical Review B 76 024518
[12] Huhtienen H, Awana V P S, Gupta A, et al 2007 Supercond. Sci. Technol. 20 159
[13] Laval J Y and Orlova T S 2003 Supercond. Sci. Technol. 16 1139