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# Determining superconducting parameters from analysis of magnetization fluctuation for CaLaBaCu$_3$O$_{7-\delta}$ superconductor

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## Abstract

In this work, we report analysis of magnetization fluctuations for the CaLaBaCu$_3$O$_{7-\delta}$ superconducting system. We describe a procedure for extracting the penetration depth $\lambda(T)$ and the coherence length $\xi$ parameters from the magnetization, as a function of the applied magnetic field. This procedure takes the vortex fluctuation into account. The data of the magnetization excess $\Delta M(T)$ are analyzed for different values of temperature in the interval from 65 to 73 K. For several magnetic fields we observed a crossover in the magnetization curves at the characteristic temperature value $T^* = 72.2$ K. We calculated the data of magnetization excess from the curves of magnetization as a function of the logarithm of the applied field. This procedure was performed for polycrystalline samples of CaLaBaCu$_3$O$_{7-\delta}$ by using the proposition of Bulaevskii, Ledvij and Kogan. We notice that the values for these superconducting parameters are in agreement with reports for high-temperature superconductors.

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*Keywords:* Superconducting parameters; Magnetization; Fluctuations

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## 1. Introduction

One of the best-adapted observables to the study of thermal fluctuation in strongly bi-dimensional high-temperature superconductors is the magnetization response for magnetic fields applied perpendicularly to the *ab* planes [1].

Below the mean-field transition temperature $T_c$, in the reversible mixed state, the excess of the magnetization, $\Delta M(T, H)$, occurs due to two main taxes: the type London diamagnetism and direct effects associated with thermal fluctuations. In the limit of weak magnetic fields, the last contribution is related to fluctuations of the positions of the vortex lines, and it is originated by fluctuations of phase of the superconducting order parameter [2]. In contrast, in the regime of strong magnetic field, the fluctuations of the width of the superconducting order parameter are essentially dominant [3]. These effects of fluctuations of phase of the order parameter are particularly important in highly anisotropic ceramic superconductors, such as Bi-, Tl- and Hg-based compounds, where the vortex lines are strongly bi-dimensional, forming weakly coupled pancakes.

The theory proposed by Bulaevskii, Ledvij and Kogan (BLK) [2] considers such bi-dimensional fluctuation effects explicitly in the free energy and into the equilibrium magnetization below the critical temperature $T_c$. For the calculation, this formalism introduces an additional term in the free energy due to the entropy caused by the thermal disorder in the vortex lattice, by using an elastic model in the one harmonic limit. This model is hardly applied in the field regime $H \ll H_{c2}(T)$, and the main result is that it predicts the existence of a temperature $T^*$, below $T_c$, for which the magnetization excess, $\Delta M(T, H)$, exhibits a clear independence of the applied field.

In this paper, we analyze the effect of the thermal fluctuations in the magnetization for polycrystalline samples of CaLaBaCu$_3$O$_{7-\delta}$, which belong to the YBa$_2$Cu$_3$O$_{7-\delta}$ family, but evidence a tetragonal structure and critical temperature below 80 K [4]. The crystalline

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characteristic of the $CaLaBaCu_3O_{7-\delta}$ system, which is similar to the Bi-, Tl- and Hg-based superconductors, permits to infer the occurrence of strong planar anisotropy.

## 2. Experimental

Samples of $CaLaBaCu_3O_{7-\delta}$ material were synthesized by the standard solid state reaction recipe, from precursor Aldrich powders of CaO (99.99%), $La_2O_3$ (99.9%), BaO (99.99%) and CuO (99.99%). Powders were mixed thoroughly, palletized and calcined at a temperature of 860 °C for 24 h. The calcined material was reground, pressed as circular discs and sintered at 900 °C for 36 h, with two intermediate pulverizations. Crystalline structure was studied by X-ray diffraction experiments, with a nickel-filtered Cu $K_\alpha$ radiation ($\lambda = 1.5406$ Å) of a SIEMENS D5000 equipment. Rietveld refinement was performed to determine the effective position of ions of Ba and Ca in the structure and the lattice parameters $a = 3.869(4)$ Å and $c = 11.615(8)$ Å. From the Rietveld refinement, it was determined that the distance between ions in $CuO_2$ is $s \approx 11.7$ Å. Magnetization measurements, $M(T)$ and $M(H)$, were performed by using a model 2000 Quantum Design Magnetic Properties Measurement System (MPMS), with a temperature precision of 0.4 K.

## 3. Results and discussion

The thermal fluctuations effects on $M(H, T)$ may be quantified through the magnetization excess, $\Delta M(H, T)$. Fig. 1 shows the data of $\Delta M(H, T)$ in the reversible mixed state for several applied magnetic fields in a sample of the $CaLaBaCu_3O_{7-\delta}$ system. In these data, we subtracted the contribution associated with the normal region, according to the equation:

$$\Delta M(H,T) = M(T,H) - M_n(T,H), \tag{1}$$

where the term $M_n(T, H)$ represents the magnetization associated with the normal contributions, i.e., magnetization above the superconducting transition. This contribution can be obtained by taking the values of the magnetization in temperature regimes above $T_c$, where the effects of fluctuations are worthless. The magnetization in the normal region was obtained by making the adjustment of experimental data for each field value applied in the interval of temperature 120–300 K. The best adjustment follows a Curie–Weiss behavior.

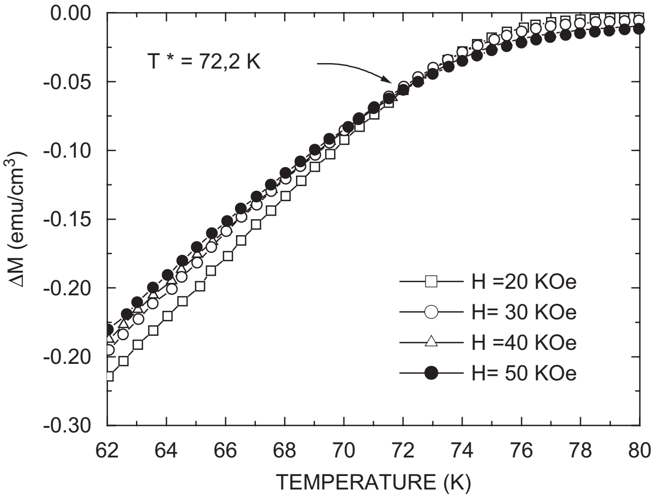

Fig. 1. Magnetization excess as a function of temperature for the $CaLaBaCu_3O_{7-\delta}$ system, in magnetic fields from 20 to 50 kOe. Curves for $H > 20$ kOe cross at the characteristic temperature $T^*$.

In Fig. 1, we can clearly observe the occurrence of a crossing of the magnetization curves for the several applied fields. This crossing has place for a characteristic temperature $T^* = 72.2 \pm 0.2$ K and for a magnetization value $M^* = 0.0542\,\mathrm{emu/cm^3}$. This result suggests that for the temperature $T^*$ the magnetization response is independent of the applied field. We applied the BKL model and used the interlayer spacing between the $CuO_2$ planes for the $CaLaBaCu_3O_{7-\delta}$ material, $s = 11.7$ Å, and the value of $T^* = 72.2 \pm 0.2$ K to determine the magnetization excess [2]

$$\Delta M^* = -\frac{k_B T^*}{\phi_0 s} = 0.41156. \tag{2}$$

Cho et al. [5] showed that the temperature of the magnetization independent of field in the polycrystalline samples happens to be $T^*$, and that the magnetization excess $\Delta M^*$ for these compounds corresponds to twice the value of the single crystal samples, e.g., $\Delta M^* = 2\Delta M_0^*$, where $\Delta M_0^* = 0.20578$ represents the single crystal magnetization independent of the applied field [3]. This discrepancy has been observed by other authors [5–7] and is attributed to the volumetric superconducting fraction present in the sample. Following the same philosophy, the volumetric fraction present in the $CaLaBaCu_3O_{7-\delta}$ sample is 26.3%, which is in agreement with the results reported in literature [5–7].

The limit of minor field, $B_{cr}$, observed for the magnetization independent of field in the $CaLaBaCu_3O_{7-\delta}$ material (Fig. 1) was 20 kOe, approximately. This value is higher than the values reported for Bi-2223 (0.1 kOe) and obtained into the framework of the BKL model, where $B_{cr}$ is given by [5,7]

$$B_{cr} = \frac{\phi}{\pi \lambda_J^2} \ln\left[\frac{\lambda_J/\xi_{ab}}{4\sqrt{\ln(\lambda_J/\xi_{ab})}}\right], \tag{3}$$

where $\xi_{ab}$ is the coherence length in the $ab$ plane, $\lambda_J = \gamma s$, and $\gamma$ is the anisotropy factor, which is slightly smaller in $CaLaBaCu_3O_{7-\delta}$ when compared with Bi-2212. Then, $\lambda_J$ is small for $CaLaBaCu_3O_{7-\delta}$ and causes the observed result in $B_{cr}$.

BLK theoretically analyze the vortex fluctuation in strongly bidimensional superconductors within the Lawrence–Doniach scheme, assuming that $H$ is applied perpendicular to the $CuO_2$ planes. By using this BLK model and considering the correction by the random orientation of grains in the polycrystalline sample [8], we write

$$\Delta M = \frac{1}{2}\frac{\phi_0}{32\pi^2\lambda_{ab}^2}\left[\ln\frac{H_{c2}\eta}{H\sqrt{e}} - g(T)\,\ln\frac{g(T)H_{c2}}{\alpha H}\right], \tag{4}$$

where $\lambda_{ab}$ represents the London penetration depth for screening by supercurrent flow in the *ab* planes, $\phi_0$ is the flux quantum and $g(T) = (32\pi^2\lambda_{ab}^2 k_B T)/(s\phi_0^2)$, where $k_B$ is the Boltzmann constant. The slope $\partial(\Delta M)/\partial(\ln H)$ is obtained as

$$\frac{\partial(\Delta M)}{\partial(\ln(H))} = \frac{1}{2}\left(\frac{\phi_0}{32\pi^2\lambda_{ab}^2(T)}\right) \times [1 - g(T)] \tag{5}$$

The first term in Eqs. (4) and (5) is known as the London term, which has validity for dense and rigid vortex systems, and the second term is due to the thermal fluctuations of vortices. In order to estimate the contribution of thermal fluctuations on the vortices $M(H)$, we can compare $g(T)$ with the unit.

We notice that to obtain the equation of London, $g(T)$ must be null. On the other hand, it is observed in Eqs. (4) and (5) that the fluctuations are more abrupt when the temperature is increased.

Fig. 2 exemplifies the magnetization excess result $\Delta M$ as a function of ln *H* for several values of temperature, in the interval from 64 to 75 K. This temperature region corresponds to the reversible magnetization regime. By fitting isothermal dates to Eq. (5), we determine $\lambda_{ab}(T)$ values. The results are presented in Fig. 3; the $\lambda_{ab}(T)$ values are also shown in the absence of thermal fluctuations, e.g., in the case of $g(T) = 0$.

In particular, when we do not consider the term due to thermal fluctuations, $\lambda_{ab}(T)$ diverges in $T^*$. For the corrected value of $\lambda_{ab}(T)$, e.g., considering thermal fluctuations, from the fitting of the Gorter–Casimir model in Fig. 3, we obtain $\lambda_{ab}(0) = 2350$ Å. By using the obtained values for $\lambda_{ab}(T)$ and Eq. (4), it is possible to determine the critical field $H_{c2}(0) = 48.3$ T for isotherms of Fig. 2. From the relation $\xi_{ab}(0) = (\phi_0/2\pi H_{c2})^{1/2}$, we find the coherence length of the $CuO_2$ planes $\xi_{ab}(0) = 26.11$ Å. At last, by the definition of the Ginzburg–Landau parameter, we obtain $\kappa = \lambda_{ab}/\xi_{ab} = 90$ for the $CaLaBaCu_3O_{7-\delta}$ system. These values are in agreement with the values obtained for other compound high-temperature superconductors [9,10].

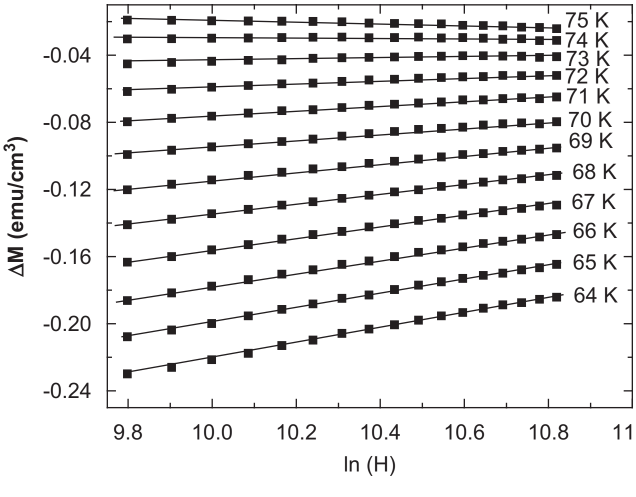

Fig. 2. Magnetization excess as a function of applied field in the low-temperature regime (64–75 K) for the $CaLaBaCu_3O_{7-\delta}$ superconductor.

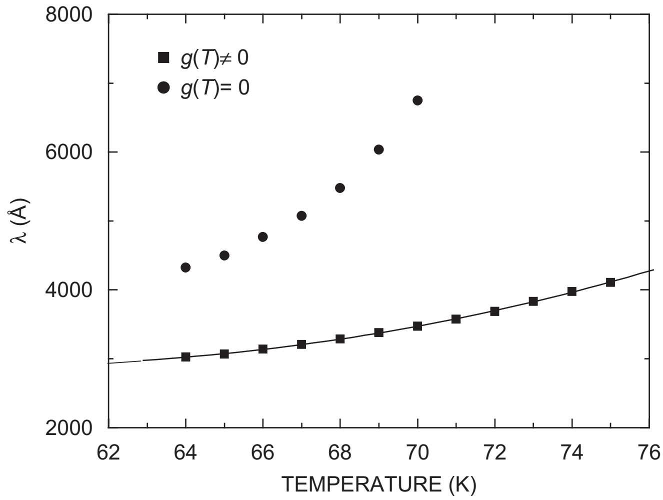

Fig. 3. Penetration depth as a function of temperature for the $CaLaBaCu_3O_{7-\delta}$ superconductor. Square points represent the penetration depth in the presence of thermal fluctuations, while circle points correspond to $g(T) = 0$. The line corresponds to the Gorter–Casimir fitting.

## 4. Conclusions

We analyze thermal fluctuations in the magnetization for the $CaLaBaCu_3O_{7-\delta}$ material by the theory proposed by BLK. Our results reveal the occurrence of the magnetization independent of field for a temperature value $T^* = 72.2 \pm 0.2$ K. By considering that this system evidences high planar anisotropy, we assume the correction by the random orientation of grains in the polycrystalline sample on the BLK model to determine the characteristic superconducting parameters: penetration depth $\lambda_{ab}$, critical field $H_{c2}$ and coherence length $\xi_{ab}$. Our results are in accordance with reports for other high-temperature superconductors.

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