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Weak field magnetic susceptibility fluctuations above the superconducting transition of $La_{0.5}Re_{0.5}BaCaCu_3O_{7-\delta}$ (Re=Y, Sm, Gd, Dy, Ho, Yb) superconductor

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We report detailed experimental results of magnetic susceptibility for the $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ superconducting system, above and close the superconducting transition. The data were obtained from 5 K up to 300 K, and applied field of 0.1 T, correspond to the so-called weak magnetic field limit. In this limit, the excess of magnetization is associated with the fluctuations of the vortex lines positions. These effects of thermal fluctuations on M_{ab} can be quantified through the known "excess of diamagnetism" $\Delta\chi_{ab.}$but T¿$T_{C.}$In this work we present a study of magnetic susceptibility fluctuations in the limit of weak magnetic fields, above the $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ (RE=Y, Sm, Gd, Dy, Ho, Yb) high superconducting material. Samples were synthesized by the standard solid state reaction. The best adjustment in the experimental data, in the limit of weak magnetic field, of $\Delta\chi$/T in function of the reduced temperature allowed to obtain the values of A_S (diamagnetism of Schmidt) and B_{LD} (parameter LD), in each one of the samples of the systems $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$. For the fluctuation analysis, we use the concept of excess of magnetization, based on the Lawrence-Doniach model (LD), which allowed to calculate the diamagnetism induced by thermal fluctuations in the normal state, in the vicinities of critical temperature T_{c0} (74, 58, 74, 55, 60, 46 K, for RE=Y, Sm, Gd, Dy, Ho, Yb respectively). It was demonstrated, by means of the analysis of the thermal fluctuations, that the $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ system shows an excellent 2D scaling behavior (B_{LD}).

Keywords: Cuprate superconductors; fluctuations; thermodynamic properties.

Reportamos resultados experimentales de medidas de susceptibilidad magnética para el sistema superconductor $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$, arriba y abajo de la transición superconductora. Los datos fueron obtenidos desde 5 K hasta 300 K, y un campo aplicado de 0.1 T, correspondiente al llamado limite de campo magnético débil. En este límite, el exceso de la magnetización es asociado con las fluctuaciones de la posición de las líneas de vórtice. Estos efectos de las fluctuaciones térmicas en M_{ab} pueden ser cualificados a través de conocido "exceso de diamagnetismo" $\Delta\chi_{ab.}$en T¿$T_{C.}$En este trabajo presentamos un estudio de las fluctuaciones de la susceptibilidad magnética en el límite de campo magnético débil, para el material superconductor $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ (RE=Y, Sm, Gd, Dy, Ho, Yb). Las muestras fueron sintetizadas por el método estándar de reacción de estado sólido. El mejor ajuste en los datos experimentales, en el límite de campo magnético débil, de $\Delta\chi$/T en función de la temperatura reducida permitió obtener los valores de la constantes, A_S (diamagnetismo of Schmidt) y B_{LD} (parámetro LD), en cada una de las muestras del sistemas $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$. Para el análisis de las fluctuaciones, usamos el concepto de exceso de magnetización, basados en el modelo de Lawrence-Doniach (LD), lo cual permitió determinar el diamagnetismo inducido por las fluctuaciones térmicas en el estado normal, en las vecindades de la temperatura critica T_{c0} (74, 58, 74, 55, 60, 46 K, for RE=Y, Sm, Gd, Dy, Ho, Yb respectivamente). Esto fue demostrado, por medio del análisis de las fluctuaciones, que muestra un excelente comportamiento scaling 2D (B_{LD}) para el sistema $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$.

Descriptores: Cupratos superconductores; fluctuaciones; propiedades termodinámicas.

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1. Introduction

High-temperature copper-oxide superconductors (HTSC) present important thermal fluctuation effects on both sides of superconducting transition. One of best adapted observables to the thermal fluctuations study in HTSC is magnetization, M_{ab}(T,H), for magnetic fields, H, applied perpendicularly to the CuO_2 planes, which is the so-called weak-amplitude limit [1-2]. High precision data of the influence of the superconducting order parameter fluctuations on the magnetization, M(T), in the weak magnetic field limit, will contribute to the understanding of the superconducting transition in copper-oxide materials [2].

In the mean field-like regime, above superconducting transition, the fluctuation-induced magnetization, ΔM, it is used to check some general aspects of the superconducting pairing state and to obtain useful relationships between some of the characteristics lengths arising in the Ginzburg-Landau descriptions of the superconducting transition [3]. Thermal fluctuations effects on M_{ab}(T,H) may be quantified through the so-called magnetization excess, ΔM_{ab}(T,H), defined as

$$\Delta M_{ab}(T,H) \equiv M_{ab}(T,H) - \Delta M_{abN}(T,H) \qquad (1)$$

where ΔM_{abN}(T,H) is the magnetization associated with the normal contributions, *i.e.*, the sample magnetization if the superconducting transitions were absent, and which may be approximated by extrapolating through the transition magnetization measured well above T_{C0}, in a temperature region where the thermal fluctuation effects become negligible [3].

Above T_{C0}, ΔM_{ab}(T,H) is only due to thermal fluctuations, which create non equilibrium cooper pairs with a finite lifetime. In turn, these fluctuations induced Coopers pairs lead to appearance of shielding currents close the transition, which round down $M(T)_H$. In HTSC, these effects are explained in terms of generalizations of the Schmidt-like approach, which takes into account the layered nature of these materials [4]. The study of ΔM_{ab} above T_{C0}, in the weak magnetic field limit or, equivalently, in the diamagnetism excess, $\Delta\chi$, may provide direct information on the Ginzburg-Landau superconducting coherence length amplitude in the ab plane $\xi_{ab}(0)$, and on the mean-field transition temperature T_{C0}. The aim of this work is to analyze susceptibility fluctuation effects in the weal-amplitude limit of high temperature superconducting oxide $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ (RE=Y, Sm, Gd, Dy, Ho, Yb), by using the Lawrence-Doniach (LD) two-dimensional (2D) model [5]. Our results reveal that fluctuations in this material have 2D character and respective critical parameters are determined from the excellent adjusting of experimental data with the LD model.

2. Experimental

Samples of $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ (RE=Y, Sm, Gd, Dy, Ho, Yb) material were synthesized by the standard solid state reaction recipe, from Aldrich precursor powders of CaO (99,99%), La_2O_3 (99,9%), BaO (99,99%), CuO (99,99%) and RE_2O_3 (99,9%). Powders were mixed, grinded, palletized and calcined at temperature of 900 ^{o}C for 24 h. Then, material was reground, pressed as circular discs and sintered at 900 ^{o}C for 36 h, with two intermediate pulverizations.

Crystalline structure was studied by x-ray diffraction experiments, with a nickel-filtered Cu-K_α radiation (λ=1,5406 Å) of a SIEMENS D5000 equipment. Rietveld refinement by using GSAS code [7] was performed to determine the effective position of Ba and Ca ions into the structure. Analysis shows that material crystallizes in a tetragonal perovskite structure, space group P4/mmm, with lattice parameters a=3.859(4) Å and c=11.645(8) Å (Fig. 1). Magnetization measurements, M(T) and M(H), were performed through a 2000-model Quantum Design Magnetic Properties Measurement System (MPMS).

3. Results and discussion

For measurements with H perpendicular to ab planes and in the weak magnetic field limit, above T_{C0}, both measured and the background magnetization arising in ΔM_{ab} of Eq. (1) depend linearly of the magnetic field amplitude. Therefore, in this case, to characterize the thermal fluctuation effects on ΔM_{abN}(T,H) it will be useful

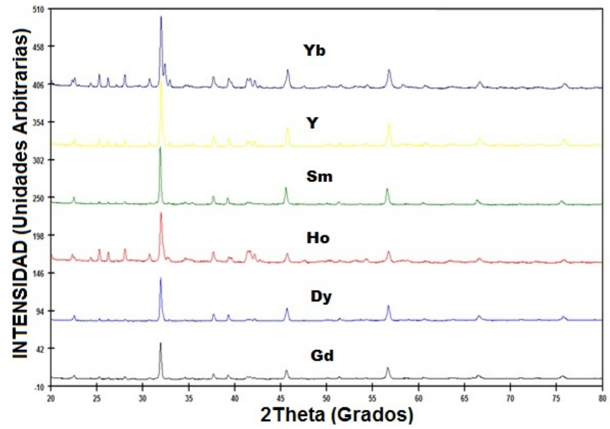

FIGURE 1. XRD espectra for $La_{0.5}TR_{0.5}Ba_2CaCu_3O_{7-\delta}$ (TR = Dy, Gd, Y, Yb, Sm y Ho).

instead of ΔM_{ab} the in-plane diamagnetism excess (also called in-plane fluctuation induced diamagnetism), $\Delta\chi_{ab}(\varepsilon)$, defined as $\Delta\chi_{ab}(\varepsilon) \equiv \chi_{ab}(\varepsilon) - \Delta\chi_{abN}(\varepsilon)$, where $\chi_{ab}(\varepsilon)=M_{ab}(\varepsilon)/H$ and $\chi_{abN}(\varepsilon)=M_{abN}(\varepsilon)/H$ are the measured and the background susceptibilities in the weak magnetic field limit, respectively, and $\varepsilon=(T-T_{C0})/T_{C0}$ represents the reduced temperature. In planar superconductors with two superconducting layers per periodic length and with two different Josephson coupling strengths, γ_1 and γ_2, between adjacent layers, in the mean-field-like temperature region and in the weal magnetic field limit $\Delta\chi_{ab}(\varepsilon)$ is given by

$$\frac{\Delta\chi_{ab}(\varepsilon)}{T} = -N_e(\varepsilon)\frac{A_S}{\varepsilon}\left(1+\frac{4B_{LD}}{\varepsilon}\right)^{-1/2} \quad (2)$$

where $N_e(\varepsilon)$ is an effective number of independent fluctuating planes per periodicity length, $A_s \equiv \pi\mu_0 k_B \xi_{ab}^2(0)/3\phi_0^2 s$ is the Schmidt diamagnetism amplitude and $B_{LD} = [2\xi_c(0)/s]^2$ is the Lawrence-Doniach parameter governing the dimensionality of thermal fluctuations of the order parameter [4]. Due the structural characteristics of $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ materials, we consider that this model is applicable for the study of diamagnetic fluctuations in them. To further analyze our experimental results on the grounds of Eq. (2), we must to use explicit expressions and values for $N_e(\varepsilon)$ and g. The approximation supposes that the strength of the Josephson coupling of each plane with it neighbor plane is the same for all planes, independently of their location. In that case, $N_e(\varepsilon)$ takes the form [3]:

$$N_e(\varepsilon) = 2\left(\frac{1+B_{LD}/\varepsilon}{1+4B_{LD}/\varepsilon}\right)^{1/2} \quad (3)$$

In the 2D limit each plane fluctuates independently $(\xi_c(\varepsilon) << s)$ and $B_{LD} << \varepsilon$. In the 3D limit $(\xi_c(\varepsilon) >> s)$ and$B_{LD} >> \varepsilon$. To compare these results with our experimental data, it is useful to rewrite the Eq. (2) by using Eq. (3) to obtain:

$$\frac{\Delta\chi_{ab}(\varepsilon)}{T} = -2\frac{A_S}{\varepsilon}\left(1+\frac{4B_{LD}}{\varepsilon}\right)^{-1/2} \quad (4)$$

Magnetic susceptibility (χ=M/H) of the

$$\mathrm{La_{0.5}Dy_{0.5}BaCaCu_3O_{7-\delta}}$$

sample measured with an applied magnetic field of 0.1 T is show in Fig. 2. The solid line represents the contribution of the magnetic susceptibility in the normal region.

For $\Delta\chi_{abN}$(T,H) measurements, samples were cooled down up to 5 K in absence of magnetic field by the known zero field cooling (ZFC) recipe. Then, magnetic field was applied and data were taken as the temperature was increased up to 250 K. The applied magnetic field of H=0.1 T corresponds to the weak magnetic field limit, where each order parameter component is expected to fluctuate independently. This limit can be to defined by the condition [4]:

$$l_H \equiv \left(\frac{\hbar}{2e\mu_0 H}\right)^{1/2} >> \xi_{ab}(\varepsilon) \qquad (5)$$

The value of T_{C0}, which was used to numerically calculate the reduced temperature, was obtained by the extrapolation of the lineal region of T/$\Delta\chi$. Figure 3 exemplifies the determination of T_{C0} as the intersection of extrapolated line with the temperature axis in a plot of T/$\Delta\chi$ as a function of temperature for the $\mathrm{La_{0.5}Dy_{0.5}BaCaCu_3O_{7-\delta}}$ sample. This procedure has been used by other authors for two-dimensional systems as Bi:2232 and Bi:2212 [2]. The diamagnetism excess above T_{C0} is presented in the Fig. 3, for $\mathrm{La_{0.5}Ho_{0.5}BaCaCu_3O_{7\delta}}$ sample. The best adjustment in the experimental data of the Eq. (2) it allowed to determine the values of B_{LD} and A_S parameters [4].

The obtained values for the B_{LD} and A_S parameters, as well as the values of T_{C0} and T_C are detailed in Table I. From Eq. (3) and the value of separation of the plane s $\approx$11.7 Å [7], we obtain $\xi_C(0)$ for all samples, which represents the coherence length associated to the fluctuational regime along c crystallographic direction. This value is approximately similar to experimentally obtained parameters of Bi-2212 and Bi-2232 superconducting systems. In the same form, by using Eq. (4), we calculate the correlation lenght of fluctuations in the ab planes, $\xi_{ab}(0)$. These results constituted the first evidence of the two-dimensional anisotropic character of the $\mathrm{La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}}$ (RE=Y, Sm, Gd, Dy, Ho, Yb).

Inset of Fig. 4 represents a linear regime in a plot of log($\Delta\chi$/T) as a function of log(ε). Slope of the linear behavior in the inset of figure 4 is x=-1. In order to establish the two-dimensional anisotropic character of the $\mathrm{La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}}$ superconducting material, we consider the 2D limit. Then we use the previously proposed expression $B_{LD} << \varepsilon$ or equivalently $\xi_c(\varepsilon) << s$. Therefore, we can to write Eq. (2) as [7,8]:

$$\frac{\Delta\chi_{ab}}{T} = -\frac{2A_s}{\varepsilon} \qquad (6)$$

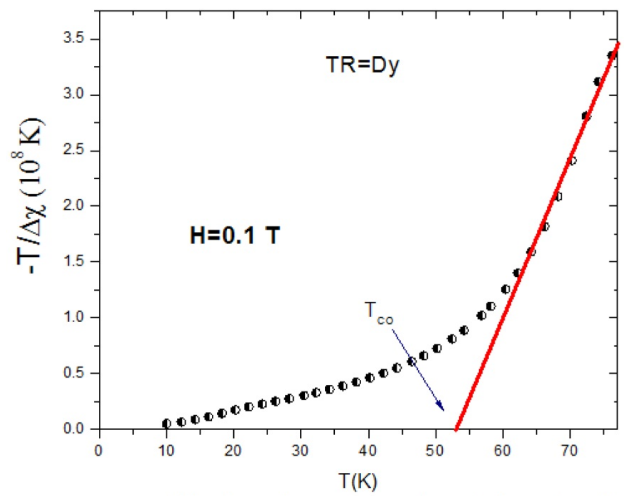

FIGURE 3. Exemplification of experimental method used to find the reduced temperature T_{c0}in the $\mathrm{La_{0.5}Dy_{0.5}BaCaCu_3O_{7-\delta}}$ sample.

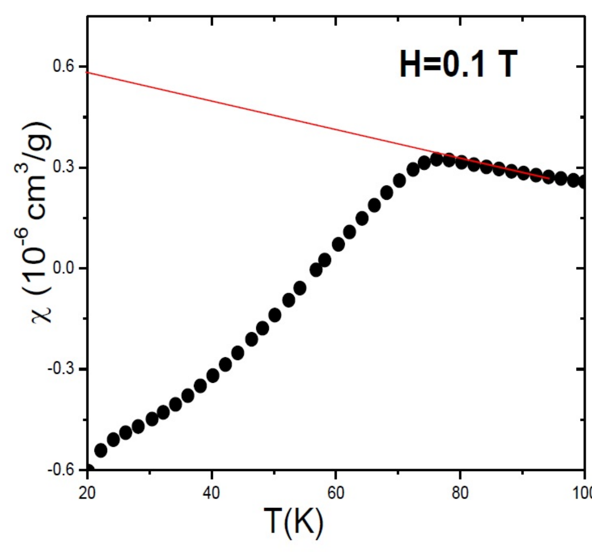

FIGURE 2. Experimental data of magnetic susceptibility for $\mathrm{La_{0.5}Dy_{0.5}BaCaCu_3O_{7-\delta}}$.

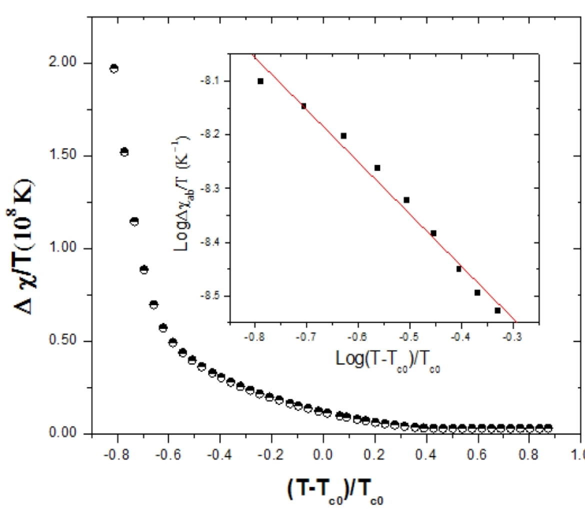

FIGURE 4. Diamagnetism excess as a function of reduced temperature for the $\mathrm{La_{0.5}Dy_{0.5}BaCaCu_3O_{7-\delta}}$ sample.

TABLE I. Critical parameters for the $La_{0.5}Re_{0.5}BaCaCu_3O_{7-\delta}$ (Re = Y, Sm, Gd, Dy, Ho, Yb) superconductor.

MUESTRA	T_{c0} (K)	T_C (K)	$B_{LD}(\times 10^{-2})$	X	$A_s(\times 10^{-8})$	$\xi_{ab}(0)$(Å)	$\xi_c(0)$(Å)
	$\pm$ 0.08	$\pm$ 0.05	$\pm$ 0.04	$\pm$ 0.02	$\pm$ 0.05	$\pm$ 0.007	$\pm$ 0.008
$La_{0.5}Y_{0.5}BaCaCu_3O_{7-\delta}$	74.00	80.02	0.58	-1.02	2.432	25.035	1.967
$La_{0.5}Sm_{0.5}BaCaCu_3O_{7-\delta}$	58.00	80.01	0.53	-1.15	1.567	20.098	1.655
$La_{0.5}Gd_{0.5}BaCaCu_3O_{7-\delta}$	74.72	80.22	0.57	-1.00	2.604	25.903	1.907
$La_{0.5}Dy_{0.5}BaCaCu_3O_{7-\delta}$	54.96	77.05	0.52	-0.97	1.074	16.636	1.581
$La_{0.5}Yb_{0.5}BaCaCu_3O_{7-\delta}$	46.37	66.14	0.58	-0.95	2.129	23.426	1.967
$La_{0.5}Ho_{0.5}BaCaCu_3O_{7-\delta}$	60.53	64.21	0.63	-1.02	2.564	25.707	2.358

In Eq. (6) it is clear that $\Delta\chi$/T varies as ε^{-1}, e.g., with an exponent x=-1. As observed in Table I, The exponent obtained by means of this adjustment for each one of the samples is consigned in the Table I, for all studied materials we obtain an x≈-1. This result confirms that $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ behaves as two-dimensional superconducting system.

4. Conclusions

$La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ (RE=Y, Sm, Gd, Dy, Ho, Yb) HTSC materials were synthesized by the solid state reaction technique. X-ray diffraction experiments shown that materials crystallized in a tetragonal perovskite structure (space group P4/mmm). From detailed susceptibility measurements we analyzed fluctuation effects close to critical temperature by means the Lawrence-Doniach model. In the limit of weak magnetic fields, results revealed that above and close the superconducting transition, $La_{0.5}RE_{0.5}BaCaCu_3O_{7-\delta}$ behaves as 2D anisotropic material. From analysis of diamagnetism excess we obtained values of critical parameters B_{LD}, $\xi_{ab}(0)$ and $\xi_c(0)$ for 2D fluctuation regime.

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