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Fluctuation phenomena in excess conductivity and magnetization of single-crystal $Bi_2Sr_2CaCu_2O_{8+y}$

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We present an analysis of the measured excess conductivity which results from the fluctuation of the superconducting order parameter of a $Bi_2Sr_2CaCu_2O_{8+y}$ single crystal and found it was fit best by the two-dimensional Aslamazov-Larkin theory. The magnetoconductivity and magnetization studies are in good agreement with the two-dimensional (2D) scaling behavior in the fremework of Lawrence-Doniach model revealing the 2D nature of the fluctuation near the mean-field transition temperature in the presence of a field.

I. INTRODUCTION

One of the important features of the high-T_c superconductors (HTSC) is the large fluctuation effects obtained well above the mean-field transition temperature, T_c. In high-T_c superconductors, the combination of short coherence length, quasi-two-dimensional (2D) structures and high operating temperatures associated with large thermal energy $\sim k_B T$ causes a large increase in the effect of thermal fluctuations. Different models were proposed to explain the high magnitude of fluctuation effects in these high-T_c superconductors. Most of the features of fluctuation phenomena in the conductivity of HTSC's are explained on the basis of Aslamazov-Larkin[1] (AL) and Maki-Thompson[2] (MT) theories. Similarly, several scaling theories have also been applied to explain magnetization in the fluctuation region.

For a highly anisotropic layered material like $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) where the anisotropy ratio $\gamma=0.02$, the fluctuation conductivity is well described[3,4] by the 2D AL theory in a wide temperature range $-4\leq\ln\epsilon\leq-2$, where $\epsilon=(T-T_c)/T_c$. However, fluctuation phenomena have been explained[5-7] in $YBa_2Cu_3O_{7-x}$ (YBCO) and in similar systems taking into account the MT theory also. For very anisotropic materials, the MT contributions, which increase the apparent width of the transition, have been ignored because they are probably absent in HTSC as a consequence of the pair-breaking effect of strong inelastic electron scattering[8] and these are treated as a very clean system because $\xi_0/1$ (where ξ_0 and 1 is the zero-temperature in-plane coherence length and electronic mean free path, respectively) is very small.

In a number of recent experimental papers, the excess conductivity in high-T_c superconductors, mostly YBCO (Refs. 5–7, 9, and 10) is well studied. Martin *et al.*[11] and Artemenko, Gorlova, and Latyshev[12] have studied some aspects of fluctuation effects near T_c in BSCCO crystal. Kes *et al.*[13] have studied magnetization measurements on BSCCO crystal and reported that diamagnetic signal increases with increasing magnetic field near T_c and above the mean-field transition temperature quasi-2D diamagnetic fluctuations are probably responsible. Very recently Calzona *et al.*[4] have studied fluctuation phenomena in BSCCO films. The fluctuations suppress the melting line in BSCCO in a field by 50 K from its mean-field transition ($\approx$90 K). However, it is reported that near T_c the fluctuation effect is dominated by a Kosterlitz-Thouless (KT) transition where the vortex-antivortex pair excitation takes place within the CuO_2 planes.[11-16] For a field greater than 1 T, vortex lattice melts at about 30 K and above this melting line, the pancake vortices in adjacent CuO_2 layers form a vortex-fluid state and their properties become very different from the fluctuation behavior of Abrikosov lattices.

In this paper, we report on the measurement of excess conductivity and magnetization of BSCCO (2212) single crystals both in zero and applied magnetic fields applied parallel to the c axis of the crystal. We argue that the excess conductivity in zero field can be well explained in the framework of 2D AL theory. The magnetoconductivity and magnetization near T_c can be successfully explained using appropriate scaling in the framework of the AL and Lawrence-Doniach models[17-19] for a 2D fluctuation.

II. EXPERIMENTAL DETAILS

High-quality single crystals used for the present studies were grown by the self-flux method. The details of the crystal growth and its characterization have been described elsewhere.[16,20] The electron-probe microanalysis and x-ray studies confirmed that the crystal is a single phase. Standard dc four-probe methods were used to determine resistance at measuring current densities less than 1 A/cm^2 having a current pulse <1 ms. Typically, we used a single crystal of $1.3\times1.00\times0.1$ mm^3 size with four evaporated silver contacts. In our magnetoresistance measurements, the absolute temperature in zero field was determined with a Rh-Fe thermometer. During a field sweep, the temperature was controlled using a capacitance sensor with a temperature accuracy better than 0.01 K. The magnetic field was applied parallel to the c

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axis and the current was sent perpendicular to the field direction. The voltage was measured to an accuracy better than 10 nV.

The magnetization measurement parallel to the c axis on the zero-field-cooled BSCCO single crystal was carried out using SQUID magnetometer (Quantum Design MPMS5) with a 4-cm scan length where the field inhomogeneity was minimum.

III. RESULTS AND DISCUSSION

A. Excess conductivity in zero field

The fluctuation conductivity in zero magnetic field described by the 2D Aslamazov-Larkin theory[1] is

$$\sigma_{\text{fl}}=\frac{e^2}{16\hbar d\epsilon}\ , \tag{1}$$

where e is the charge of electrons and d is the distance between the superconducting CuO_2 layer (≈ 15 Å for the BSCCO crystal). In the above equation, the model of Gaussian fluctuations, where the free energy of the fluctuation is lower than the thermal energy, is considered. This phenomenon is considered in the temperature region very close to T_c of BSCCO. Here the MT contribution is not considered because of the large anisotropy of the system as discussed in Sec. I. Figure 1 shows the excess conductivity vs reduced temperature, ϵ, in a log-log scale. σ_{fl} was evaluated from $(\rho_N-\rho/\rho_N)$, where ρ_N is the normal-state resistivity and ρ is the resistivity at the temperature of measurement. ρ_N was determined from about 2 K above T_c to 240 K $\gg 2T_c$ to find σ_{fl}. A very good agreement with Eq. (1) is observed for temperatures $-3.5\leq\ln[(T-T_c)/T_c]\leq-1.5$. The best fit of conductivity data above 88 K with Eq. (1) gives the mean-field transition temperature $T_{c0}\approx 86.5\pm0.5$ K and a reasonable estimate of interlayer distance ≈ 15 Å. If we go to a temperature sufficiently far from T_c, i.e., $\ln[(T-T_c)/T_c]\geq -1.5$, the AL theory does not hold good and experimental curve deviates from Eq. (1)

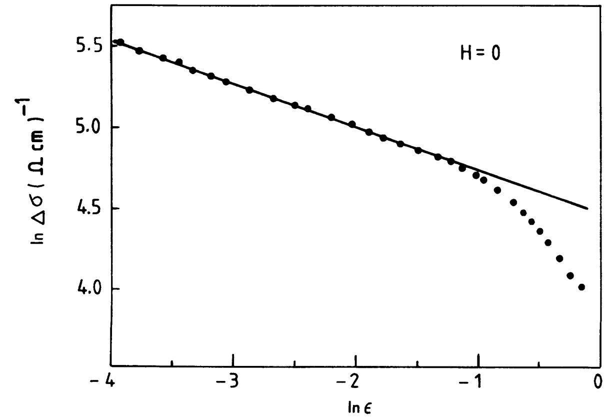

FIG. 1. Excess conductivity vs reduced temperature ϵ in zero field. The solid line is a theoretical fitting curve according to the Aslamazov-Larkin 2D scaling.

(shown as a solid line).

The functional form of the excess conductivity for a 3D system is

$$\sigma_{\text{fl}}=\frac{e^2}{32\hbar\xi(0)\epsilon}\ , \tag{2}$$

where $\xi(0)$ is the zero-temperature coherence length. We fitted our data to the above equation and obtained a very small value of $\xi(0)\approx 1-2$ Å. This seems unreasonable and too small to induce superconductivity in the c direction and rules out the validity of 3D thermal fluctuations of superconducting order parameters for explaining the excess conductivity. Further, if we consider the interlayer coupling due to Josephson tunneling phenomena proposed by Lawrence and Doniach,[17] the 2D-3D crossover temperature, $T_{Cr}=T_C^{mF}\exp[2\xi(0)/d]^2$ is ≈ 87.4 K which is within the Ginzburg criterion where the mean-field theory breaks down.

B. Magnetoconductivity and magnetization

Critical fluctuations in HTSC are studied theoretically by Ullah and Dorsery,[18,19] Tesanovic *et al.*[21] and Ikeda, Ohmi, and Tsuento[22] based on the Lawrence-Doniach model,[17] Kim, Gray, and Trochet[7] have successfully analyzed the fluctuation conductivities in magnetic fields in YBCO and Tl-based superconductors using the above[18,19] 2D and 3D scaling function in the critical region. In the framework of the above model, both magnetoconductivity and magnetization can be expressed in 2D or 3D using the following scaling forms. These are

$$\sigma(H)_{2\text{D}}=\left[\frac{T}{H}\right]^{1/2} f_{2\text{D}}\left[A\frac{T-T_c(H)}{(TH)^{1/2}}\right] \quad \text{for 2D}\ , \tag{3}$$

$$\sigma(H)_{3\text{D}}=\left[\frac{T^2}{H}\right]^{1/3} f_{3\text{D}}\left[B\frac{T-T_c(H)}{(TH)^{2/3}}\right] \quad \text{for 3D}\ . \tag{4}$$

Here A and B are appropriate constants characterizing the materials and $f_{2\text{D}}$ and $f_{3\text{D}}$ are unspecified scaling functions. According to this model, any physical property including magnetization, M, will follow the same scaling behavior. The AL term has been taken into account in the above equations. The plot $\sigma(H)(H/T)^{1/2}$ vs $[T-T_c(H)]/(TH)^{1/2}$ for 2D and its respective plot for 3D will determine the validity of scalings.

The most important parameter in Eqs. (3) and (4) is to determine the mean-field transition temperature in the presence of magnetic field, $T_c(H)$. According to Ginzburg-Landau theory, the shift is described by

$$\ln\left[\frac{T_{c0}}{T_c(H)}\right]=\frac{H}{T_c(H)}\left[\frac{dH_{c2}}{dT}\right]_{T_{c0}}\ . \tag{5}$$

The correct determination of T_{c0} can well define dH_{c2}/dT and these two are major parameters for fitting. We have taken $T_{c0}=87$ K and $dH_{c2}/dT\approx -2.2$ T/K for magnetoconductivity plot. Figure 2 shows the excess magnetoconductivity vs temperature and the inset in Fig. 2 shows clearly how resistance is increased with increasing field. Figure 3 shows the scaling plot for BSCCO in

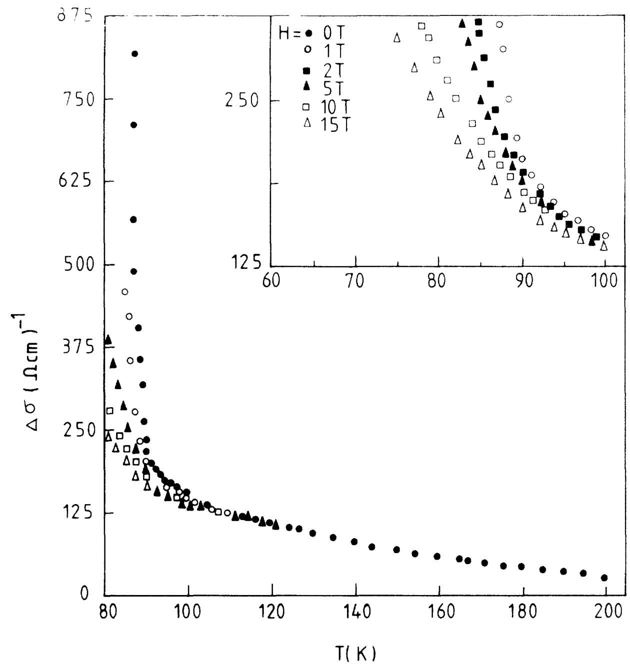

FIG. 2. Excess magnetoconductivity at various magnetic fields vs temperatures. The inset shows clearly the transition region.

the 2D model. The scaling is very sensitive to the choice of T_{c0} and we found the best fit for $T_{c0} \approx 87+2$ K for 2D. However, a noticeable spreadout begins towards the low-temperature region for field for 1–10 T. This region is dominated by field-induced broadening of resistivity. The scaling for 3D remains poor even after a good deal of adjustment of T_{c0} in the region 85–92 K and dH_{c2}/dT in -1.5 to -4 T/K.

Figure 4 shows magnetization of the BSCCO crystal near T_c. As the magnetic field applied along the c axis is increased, diamagnetism onset gradually becomes wide and rounded. It is noted that the diamagnetic moment near T_c increases with increasing magnetic field in a nonlinear manner and below T_c diamagnetic signals become

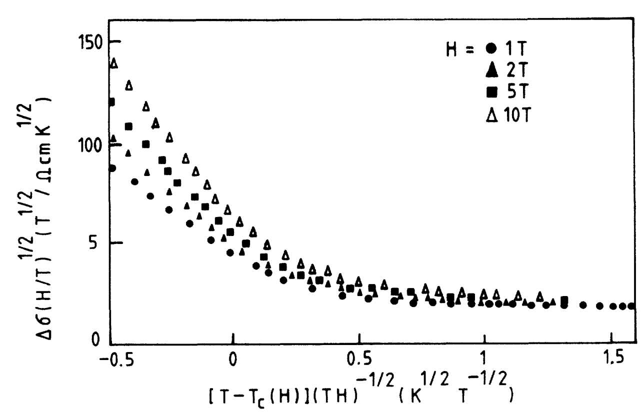

FIG. 3. 2D scaling of the fluctuation magnetoconductivity of BSCCO crystal.

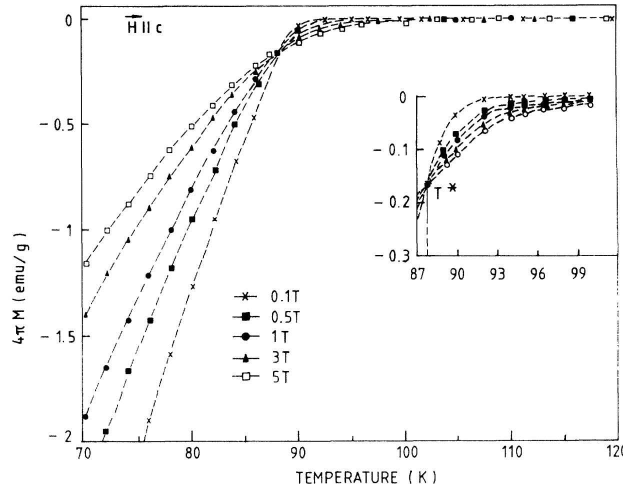

FIG. 4. The temperature dependence of the magnetization of the BSCCO crystal measured at various fields. The increased diamagnetic signal with increasing field and crossover temperature, T^*, is clearly shown in the inset.

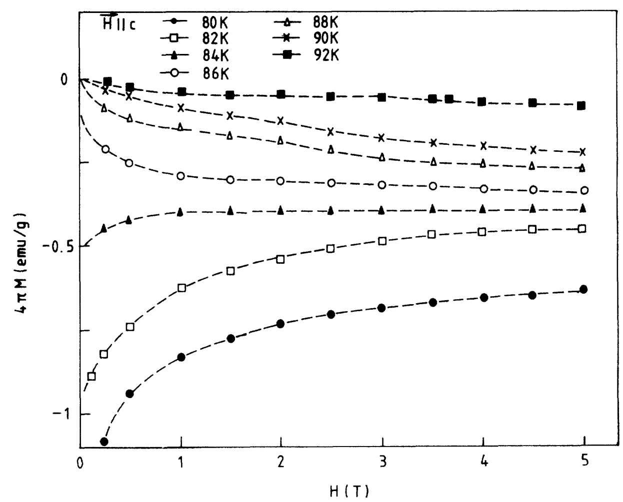

FIG. 5. The magnetization vs magnetic field measured at various temperatures near the transition temperature.

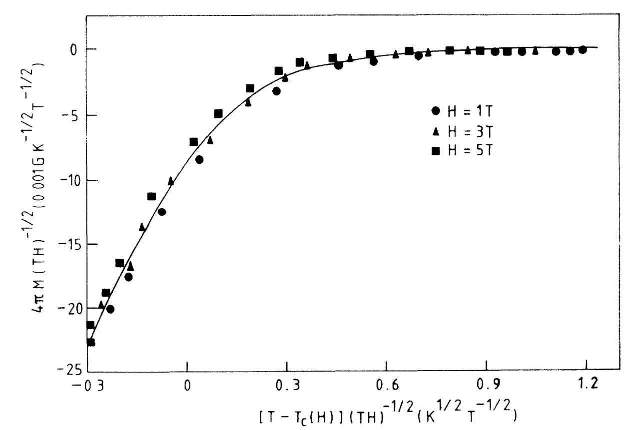

FIG. 6. 2D scaling of the magnetization data using the scaling relation discussed in the text. The solid line is a theoretical fit to the 2D scaling.

smaller in large magnetic fields. This phenomena is inconsistent with GL theory in the vortex state near T_c. This effect has already been explored by Kritscha et al.[23] However, this effect is small in lower fields (<0.05 T). The inset in Fig. 4 shows clearly the crossover temperature $T^* \approx 88$ K which is in very good agreement with the result of Kes et al.[13] It should be noted that in Fig. 4, the background signal is corrected by subtracting the magnetic moment at 120 K.

Figure 5 shows a fast increase of diamagnetic signal which levels off at about 1 T and remains almost constant up to 5 T. In Fig. 5, it is very clear that above $T^* = 88$ K, the signal increases with increasing magnetic field which suggests strong fluctuation effects in this temperature range. Recently Grover et al.[24] have also shown some anomalous magnetization behavior in this crossover temperature region of BSCCO (2212) crystal.

Figure 6 shows the 2D scaling of the magnetization data (of Fig. 4) of the BSCCO crystal using Eq. (3) substituting for magnetization. The only adjustable parameters involved are T_{c0} and dH_{c2}/dT out of which T_{c0} is found extremely sensitive for scaling. The best fit is for $T_{c0}=90$ K and $dH_{c2}/dT = -2.7$ T/K, and excellent agreement between theory and our data is clearly illustrated in Fig. 6. However, using Eq. (4) for the 3D scaling poor agreement was obtained with various values of T_{c0} and $T_c(H)$.

In conclusion, we have studied the excess conductivity of the BSCCO crystal both in zero-field and in various magnetic fields oriented parallel to the c axis. In zero field, the excess conductivity strictly obeys the 2D Aslamazov-Larkin theory. The magnetoconductivity also supports the 2D scaling relation using the Lawrence-Doniach model. The magnetization measurements reveal a crossover temperature, T^*, above which large fluctuation effects were observed and in low fields the effect is drastically small. In moderately low fields, the effects are due to the phase fluctuation of order parameters and in high fields (>0.1 T), fluctuation effects are mainly caused by the amplitude fluctuations of order parameters. A careful scaling relation using available theory for magnetization suggests the 2D nature of the fluctuation near the mean-field transition temperature region.

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