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# Evidence of critical fluctuations from the magnetoconductivity data in $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ phase

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**Abstract.** The fluctuation-induced magnetoconductivity of the $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ phase is studied above zero-field critical temperature $T_c(0)$ and for moderate magnetic fields. It is found that the Gaussian approximation for superconducting fluctuations underestimates the negative fluctuation magnetoconductance drastically in the $T_c(0) < T < T_c(0) + 20$ K temperature range. Taking into account the critical fluctuation contribution on the base of self-consistent Hartree approximation makes it possible to explain the data quantitatively in terms of the only Aslamazov-Larkin contribution for different magnetic fields and temperatures, consistently with the zero field data.

**PACS.** 74.25.Fy Transport properties (electric and thermal conductivity, thermoelectric effects, etc.) – 74.40.+k Fluctuations (noise, chaos, nonequilibrium superconductivity, localization, etc.) – 74.72.Hs Bi-based cuprates – 74.76.Bz High-$T_c$ films

A wide region of fluctuation-induced behavior, extended well above the zero-field transition temperature, is one of the most interesting features of the high-temperature superconductors (HTS). The unit volume of fluctuation is determined by coherence lengths, very short in the case of cuprates. At the same time, each fluctuation mode is associated with a thermal energy of $\sim k_B T$, much larger than in the case of conventional superconductors, which results in the enhanced density of fluctuation-induced free energy. Additionally, the layered structure of conducting Cu-O planes reduces the effective dimensionality of system with a further enhance of fluctuation compared to the three-dimensional case. The fluctuation effects were found to be responsible for numerous anomalies in the normal-state properties of HTS, including the enhancement of out-of-plane conductivity at the edge of transition, the negative magnetoresistance along $c$-axis, the pseudogap-like anomalies in far-infrared conductivity, the non-Korringa behavior of NMR rate and others (for a comprehensive review see [1]). Usually, the interpretation of experimental data in terms of fluctuation theory requires the extrapolation of the normal-state property from high temperatures (at least $T \sim 2\,T_c(0)$), where fluctuation effects are supposed to be negligible. As most of the normal-state properties of HTS are temperature-dependent, this procedure is somewhat arbitrary. Moreover, recent studies demonstrated that fluctuation effects in HTS may persist up to quite high temperatures [2,3] and extrapolation of normal-state property becomes doubtful. The above-mentioned problem may be resolved by studying a property such as fluctuation magnetoconductivity (MC), where the field-independent normal-state contribution is canceled. Fluctuation MC of different HTS families has been extensively studied before and the general agreement with the full theory of fluctuation conductivity in the presence of magnetic field perpendicular to layers [4] has been found. At the same time, some authors [5,6] have mentioned that the predictions of fluctuation theory often underestimate the magnitude of negative fluctuation-induced MC in the intermediate field range, even in the order of magnitude, when temperature is about 10 K above $T_c(0)$. To improve the agreement the authors used additional corrections, like the Maki-Thompson, the Zeeman terms and the normal-state MC, or took into account the non-uniform critical temperature distribution inside the sample [2,5,6]. Considering these additional contributions leads to the increase of the number of free fitting parameters and, therefore, to the less reliable results of such analysis. It is interesting that, to fit the zero-field excess conductivity by the fluctuation theory, no additional contributions are required and the only Aslamazov-Larkin (AL) term (paraconductivity) provides a very good fit to the data in all cases [3]. The deviation of the fluctuation MC data from the Gaussian theory predictions [4,7,8] could result from approaching the region of critical fluctuations, where correction terms of higher order

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in the superconducting order parameter, $\psi$, are not negligible in the Ginzburg-Landau free energy. In the Gaussian approximation, which theory [4] is based on, fluctuations are considered to be independent and only the $|\psi|^2$ terms are included. Hence, the Gaussian fluctuation theory works well for temperatures high enough in comparison with $T_c(0)$ where fluctuations are small in magnitude. Therefore, it is quite natural to observe a deviation of experimentally measured fluctuation conductivity from the Gaussian theory as $T$ approaches $T_c(0)$. The width of critical region in the absence of magnetic field is determined by the so-called Ginzburg number, $Gi$, which, for the quasi-two-dimensional case may be expressed through the specific-heat jump, $\Delta C$, as $Gi = k_B/(\Delta C\ \xi^2_{||}(0)\ s)$. Assuming the value coming from Ginzburg-Landau theory: $\Delta C = 0.35(p_F m/\hbar^3)T_c k_B^2$, one gets that $Gi$ is roughly the ratio between the critical temperature and the Fermi energy, $kT_c(0)/E_F$. For quasi-two-dimensional Bi- and Tl-based compounds $Gi$ can reach 0.05, and, therefore, the region of reduced temperatures $\epsilon = (T - T_c(0))/T_c(0)$ where Gaussian approximation may be used, is $0.05 \ll \epsilon \ll 1$, which means that $T$ should be at least $15 \div 20$ K above $T_c(0)$. A magnetic field $B$ applied perpendicular to layers further increases the critical region because its width becomes proportional to $\sqrt{B}$. Ikeda, Ohmi and Tsuneto [9] calculated the fluctuation conductivity in Lawrence-Doniach model but they included the $|\psi|^4$ term in the Ginzburg-Landau free energy. Later on, the similar problem was considered by Ullah and Dorsey [10] who included a $|\psi|^4$ term within the self-consistent Hartree approximation and obtained fluctuation-induced corrections to the transport coefficients, including electrical conductivity, in magnetic field. The scaling relations for fluctuations MC in the lowest Landau level approximation, calculated in reference [10], were found to be consistent with experimental data on $YBa_2Cu_3O_x$ and $Tl_2Ba_2CaCu_2O_x$ in reference [11]. Recently, it was shown that both inplane and out-of-plane components of magnetoconductivity tensor of $Bi_2Sr_2CaCu_2O_x$ films are well described in terms of the fluctuation theory within the Hartree approximation in a wide range of temperatures below $T_c(0)$ [12]. In the present paper we study the fluctuation MC in $Bi_2Sr_2Ca_2Cu_3O_x$ above $T_c(0)$. The AL contribution to inplane electrical conductivity in the presence of transverse magnetic field is given by [4]:

$$\sigma_{ab}^{\mathrm{AL}}(B) = A\sum_{n=0}^{\infty} \frac{n+1}{[(\epsilon_B+\beta(n+1))(\epsilon_B+\beta(n+1)+r)]^{1/2}} + \frac{n+1}{[(\epsilon_B+\beta n)(\epsilon_B+\beta n+r)]^{1/2}} - \frac{2(n+1)}{[(\epsilon_B+\beta(n+\frac{1}{2}))(\epsilon_B+\beta(n+\frac{1}{2})+r)]^{1/2}} \tag{1}$$

where $A = 370/s$ [Ohm cm]$^{-1}$, $s$ being the spacing between $CuO_2$ planes measured in angstroms. $r = 4\eta J^2/v_F^2$ is the parameter characterizing dimensional crossover in fluctuation behavior with $r(T_c) = 4\xi_\perp^2(0)/s^2$, $\xi_\perp^2(0)$ being the zero-temperature Ginzburg-Landau coherence length in the $c$-axis direction. $J$ is the effective quasiparticle hopping energy and $v_F$ being the Fermi velocity parallel to layers, whereas $\eta$ is the coefficient of the gradient term in the 2D Ginzburg-Landau theory defined in reference [4]; $\beta$ is defined as $2B/[T_c|\mathrm{d}H_{c2}/\mathrm{d}T|_{T_c}]$. The temperature scale is defined by the parameters $\epsilon = t-1,\ t = T/T_c(0),\ \epsilon_B = \epsilon + \beta/2$. To modify this equation within the Hartree approximation, one has to renormalize $\epsilon_B$ according to self-consistent equation [10]:

$$\epsilon_B = \tilde{\epsilon}_B - \frac{1}{4}\ Gi^2\ t\ \beta \times \sum_{n=0}^{1/\beta} \frac{1}{[(\tilde{\epsilon}_B+\beta n)(\tilde{\epsilon}_B+\beta(n+1)+r)]^{1/2}}\,. \tag{2}$$

The fluctuation conductivity in the Hartree approximation may be obtained now by replacing $\epsilon$ with $\tilde{\epsilon}$ in equation (1). The sample used in the experiment is a $Bi_2Sr_2Ca_2Cu_3O$ tape prepared by the powder in tube method which is described elsewhere [13]. It is well known that this compound has never been obtained as a single crystal and this procedure provides filaments ($10 \div 30\ \mu$m) of strongly connected superconducting grains with excellent intrinsic properties. This is confirmed by X-ray diffraction patterns which contain only the $(00l)$ peaks of the 2223 phase [14]; secondary phases, between them the 2212 phase, if present at all, must constitute less than 5%. Moreover the filament is strongly textured with the $c$-axis oriented perpendicular to the tape plane (rocking angle of 8°). Concerning a possible nonuniform critical temperature, it is mainly due to a distribution of the Pb content in the (2223) phase. On the other hand, in thermodynamical samples the Pb content cannot be varied easily; in reference [14], only varying dramatically the reaction time, the Pb content has been changed from 1.9 to 1.3 at%, with a shift in the critical temperature less than 2 K. Therefore, much narrower critical temperature distribution is expected in samples as our, grown in optimal condition. The resistivity measurements were performed, after removing the silver sheathing chemically, by a standard four probes technique using a Keithley 182 nVoltmeter; the sensitivity of the measurements was 10 p.p.m. The resistivity was measured each 0.1 K increasing the temperature from 100 to 300 K; the magnetoresistivity measurements were performed at a fixed magnetic field and increasing the temperature from 100 to 200 K. Figure 1 shows the magnetoresistivity measurements from 105 to 130 K at magnetic fields of 0, 0.04, 2, 4, 8 T. The good quality of the sample is emphasized by the low resistivity values, of the same order of magnitude as those measured in HTS single crystals. In zero field the zero resistivity state is reached at 108.6 K and above this temperature the transition is rounded by fluctuations and by some critical temperature distribution: we define $T_c$ and $\Delta T_c$ as the maximum and the half width at half-height of the $\mathrm{d}\rho\mathrm{d}T$ *versus* $T$ curve. We find $T_c = 109.3$ K and $\Delta T_c = 0.4$ K: such a critical temperature nonuniformity limits our analysis at reduced temperature larger than $\Delta T_c/T_c \sim 0.0036$.

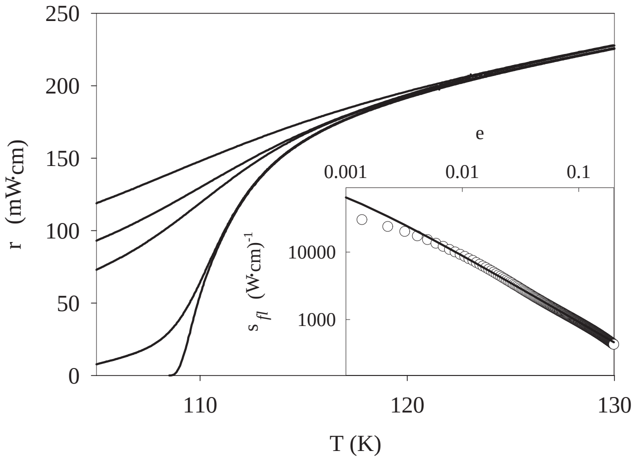


**Fig. 1.** Magnetoresistivity measurements from 105 to 130 K at the magnetic fields of 0, 0.04, 2, 4, 8 T. In the inset the excess conductivity at zero field $\sigma_{\text{fl}}$ is shown as a function of $\epsilon$: the experimental data (circle) are compared with the quasi-two-dimensional AL formula (continuous line).

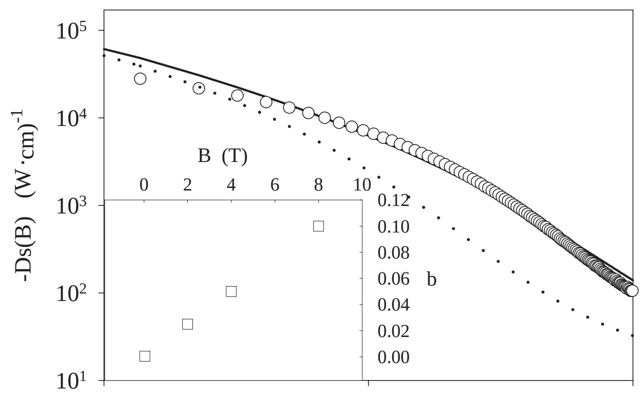


**Fig. 2.** Magnetoconductivity $\Delta\sigma(B) = \sigma(B) - \sigma(0)$ *versus* $\epsilon$ for $B = 8$ T: the circles are the experimental data, the continuous line is the fit from equations (1) and (2) and the dotted line is the Gaussian approximation without renormalization (Eq. (1) with $\beta = 0.1$ and $r = 0.001$). The $\beta$ values obtained by the best fit procedure are shown in the inset as a function of the applied magnetic field.

In the inset of Figure 1 the zero-field excess conductivity $\sigma_{\text{fl}} = (\rho_n - \rho)/\rho_n\rho$ is plotted as a function of $\epsilon$. Here $\rho_n$ is the normal state resistivity linearly extrapolated at temperature as high as $T > 2T_c(0)$. Comparison of $\sigma_{\text{fl}}$ with quasi-two-dimensional AL formula is shown in the inset of Figure 1 (continuous line). From the best fit $T_c(0)$ has been found to be 109.3 K, which corresponds exactly to the maximum of $\mathrm{d}\rho/\mathrm{d}T$, the anisotropy parameter $r$ has turned out to be 0.001, and the prefactor $A$ is 92.5 $\Omega$ cm, corresponding to $s = 16.4$ Å to be compared with an interlayer distance of 18 Å. As expected, the parameter $r$ is smaller than what was found in the less anisotropic YBCO compounds (0.01–0.1) [15]. Moreover, the good agrement with the interlayer distance confirms that resistivity data are not affected by extrinsic effects such as weak link dissipation which causes a decrease of the measured $\sigma_{\text{fl}}$ [15]. The finite-field data were then fitted to equations (1) and (2) by keeping $T_c(0)$, $r$ and $A$ fixed and $\beta$ and $Gi$ as free parameters. For intermediate fields of 2, 4 and 8 T the fit is generally good, providing field-independent $Gi$ in the range $0.08 \div 0.1$. On the other hand, $\beta$ was found to vary linearly with the applied field, as expected; consistently, it yields a slope of the upper critical field of about 1.5 T/K at $T_c$, to be compared with the thermodynamic $|\mathrm{d}H_{c2}/\mathrm{d}T|_{T_c} \approx 2 \div 3$ T/K obtained earlier from magnetization data [16]. All these results are emphasized by Figure 2 where, as an example, $\Delta\sigma(B) = \sigma(B) - \sigma(0)$ *versus* $\epsilon$ is reported for $B = 8$ T: the circles are the experimental data, the continuous line is the fit from equations (1) and (2), and the dotted line is the Gaussian approximation without renormalization (Eq. (1)). $\beta$ as a function of the applied magnetic field is shown in the inset of Figure 2. As we can see, the magnetoconductivity data are well described by taking the critical fluctuation into account exactly in the region ($0.001 < \varepsilon < 0.1$) where Gaussian approximation without renormalization underestimates the negative fluctuation magnetoconductivity. This discrepancy was pointed out in references [5,6], but was attributed to the presence of additional contributions; on the other hand in reference [17] the agreement with the Gaussian approximation was proved at larger temperatures.

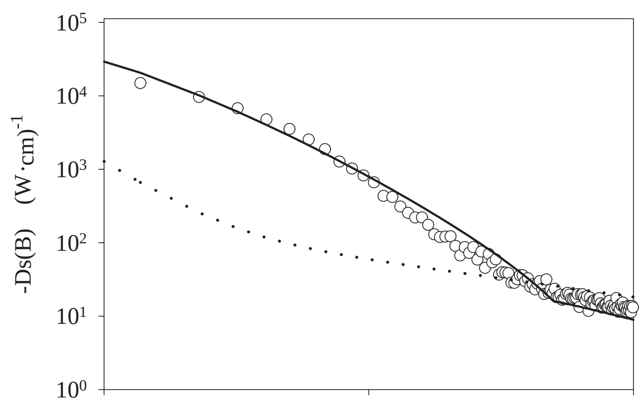


**Fig. 3.** Magnetoconductivity $\Delta\sigma(B) = \sigma(B) - \sigma(0)$ *versus* $\epsilon$ for $B = 0.04$ T: the circles are the experimental data, the continuous line is the fit from equations (1) and (2) and the dotted line is the Gaussian approximation without renormalization (Eq. (1) with $\beta = 0.0005$ and $r = 0.001$).

The disagreement between the Gaussian approximation and experimental data at small $\varepsilon$ is even more pronounced in a field as low as 0.04 T, where the Gaussian contribution, being quadratic in the magnetic field, is roughly two orders of magnitude less than the experimentally measured fluctuation magnetoconductivity. The calculation according to the Hartree approximation with appropriate $\beta = 0.0005$ and $Gi = 0.1$ gives a magnitude nearly twice as big as experimentally observed.

The best fit to the 0.04 T data (shown in Fig. 3) is found for $\beta = 0.0005$ and $Gi = 0.03$, the latter being three times lower than the value found above for 2, 4 and 8 T. We can say that for weak magnetic fields the renormalized theory is only in qualitative agreement with the data. For comparison, the result of calculation according to the fluctuation theory within the Gaussian approximation is shown in Figure 3 as a dotted line. One can observe that the Gaussian approximation underestimates the magnitude of fluctuation magnetoconductivity by two orders of magnitude when temperature approaches the transition, while the renormalized theory is in good agreement with data. Discussing the results obtained we want to point out that the experimentally measured magnetoconductivity of $Bi_2Sr_2Ca_2Cu_3O_x$ phase may be described quantitatively (except for magnetic field as low as 0.04 T) in terms of the Aslamazov-Larkin theory modified by the Hartree renormalization for finite magnetic field and no additional contributions are required in order to achieve a good agreement between theory and experimental data. As we already discussed, the magnetoresistivity measurements provide a useful tool for studying fluctuation phenomena because in this case the problem of extrapolation of normal-state resistivity from high temperatures does not appear. In our discussion we have not considered the negative magnetoconductivity due to the curvature of the trajectories of normal-state quasiparticles. In the relative vicinity of $T_c$, however, owing to the strong singularity of fluctuation MC, the normal-state MC can be omitted. Actually, the order of magnitude of fluctuation MC is: $\Delta\sigma_{\rm fl}/\sigma_n \sim Gi(\frac{\beta}{\epsilon})^2\frac{1}{\sqrt{\varepsilon}} \sim Gi\frac{1}{\varepsilon^{3/2}}(\frac{\omega_c}{T})^2$, where $\omega_c$ is the cyclotron frequency, while the classical normal-state MC $\Delta\sigma_n/\sigma_n \sim (\omega_c\tau)^2$. One can easily define the condition under which the normal-state MC can be neglected: $\epsilon < \frac{Gi^{2/3}}{(T\tau)^{4/3}}$. If the Ginzburg number is of order of 0.1 and $T\tau$ is about unity this condition reads $\epsilon < 0.2$, *i.e.* in the very range we considered. At higher temperatures the normal-state MC should be accounted together with the fluctuation-induced MC. Naturally, if the material is dirty enough and $T\tau < 1$ (as it is believed for the $Bi_2Sr_2Ca_2Cu_3O_x$ phase), the region of reduced temperatures where the normal-state MC is negligible would be wider according to the above relations.

To summarize, we have measured the fluctuation-induced MC in $Bi_2Sr_2Ca_2Cu_3O_x$ phase and we have shown the quantitative agreement of our data with the Aslamazov-Larkin theory of fluctuation magnetoconductivity with the Hartree renormalization.

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