Evidence of critical fluctuations from the magnetoconductivity data in Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+x}$ phase

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Abstract. The fluctuation-induced magnetoconductivity of the Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+x}$ 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 $T \sim 2T_c(0)$), 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, \( G_i \), which, for the quasi-two-dimensional case may be expressed through the specific-heat jump, \( \Delta C \), as \( G_i = k_B/\langle \Delta C \xi^2(0) \rangle \) s. Assuming the value coming from Ginzburg-Landau theory: \( \Delta C = 0.35(\nu_T m^*k_B)^2 \), one gets that \( G_i \) 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 \( G_i \) 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 \( 15 \pm 20 \) 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 Tsumoto [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\(_2\)Cu\(_3\)O\(_y\) and Tl\(_2\)Ba\(_2\)Ca\(_2\)Cu\(_3\)O\(_x\) in reference [11]. Recently, it was shown that both in-plane and out-of-plane components of magnetoconductivity tensor of Bi\(_2\)Sr\(_2\)Ca\(_2\)Cu\(_3\)O\(_y\) 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\(_2\)Sr\(_2\)Ca\(_2\)Cu\(_3\)O\(_y\), above \( T_c(0) \). The AL contribution to in-plane electrical conductivity in the presence of transverse magnetic field is given by [4]:

\[
e_{\text{AL}}(B) = A \sum_{n=0}^{\infty} \left[ \frac{n+1}{(\epsilon_B + \beta(n+1))(\epsilon_B + \beta(n+1) + r)} \right]^{1/2} + \frac{n+1}{2(n+1)} \left[ \frac{1}{(\epsilon_B + \beta(n + \frac{1}{2}))(\epsilon_B + \beta(n + \frac{1}{2} + r))} \right]^{1/2}
\]

where \( A = 370/\text{s [ohm cm]}^{-1} \), \( s \) being the spacing between CuO\(_2\) planes measured in angstroms, \( r = 4nJ^2/v_F^2 \) is the parameter characterizing dimensional crossover in fluctuation behavior with \( r(T_c) = 4\xi^2(0)/s^2, \xi^2(0) \) 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 \( 2B/|T_c|dH_{c2}/dT|_{T_c} \). 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]:

\[
\epsilon_B = \frac{1}{4}G_i^2 t \beta \times \frac{1}{\sum_{n=0}^{\infty} \left[ (\epsilon_B + \beta n)(\epsilon_B + \beta(n + 1 + r)) \right]^{1/2}}.
\]

The fluctuation conductivity in the Hartree approximation may be obtained now by replacing \( \epsilon \) with \( \epsilon_B \) in equation (1). The sample used in the experiment is a Bi\(_2\)Sr\(_2\)Ca\(_2\)Cu\(_3\)O 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 < 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\(^\circ\)). 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, with 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 \( \Delta \rho/dT \) 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 \( \Delta T_c/T_c \sim 0.0036 \).