Paraconductivity of underdoped $La_{2-x}Sr_xCuO_4$ thin-film superconductors using high magnetic fields

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The contribution of superconducting fluctuations to the conductivity, or paraconductivity, is studied in the underdoped regime of $La_{2-x}Sr_xCuO_4$ cuprates. A perpendicular magnetic field up to 50 T is applied to suppress the superconductivity and obtain the normal state resistivity, which is then used to calculate the paraconductivity. Surprisingly enough, it is consistent with a two-dimensional Aslamazov-Larkin regime of Gaussian fluctuations close to the critical temperature. At higher temperature, the paraconductivity exhibits a power-law decrease in temperature (as $T^{-\alpha}$), as was previously shown for underdoped $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples. Our observations are not consistent with the existence of Kosterlitz-Thouless fluctuations. This tends to indicate that the superconducting pair amplitude is not already defined above T_C in the pseudogap state.

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I. INTRODUCTION

High-T_C cuprate superconductors are known to exhibit a depression in the density of states, often referred to as the "pseudogap." This feature, firstly discovered by NMR[1] and also observed in the specific heat,[2] takes place below the so-called pseudogap temperature T^*, only in the underdoped part of the phase diagram. The energy of this pseudogap compares with the superconducting gap, as observed in scanning tunneling microscopy experiments;[3] ARPES experiments have established its angular dependence, evocative of the superconducting gap symmetry itself.[4]

The different scenarios which attempt to account for this phenomenon may be separated into two classes. A first class of models attributes this feature to a "precursor pairing." Since the phase stiffness is low in these compounds, Cooper pairs may form at the pseudogap temperature (T^*), well above T_C without acquiring long range phase coherence, and then condense at T_C.[5] In some recent experiments, the observation of a large Nernst signal above T_C has been attributed to the existence of vortices, seeming to plead in favor of this scenario.[6] However, Ussishkin *et al.*[7] have calculated the Nernst signal expected in the case of phase fluctuations and do not find it consistent with the observations. A second class of models attributes this pseudogap phase to a competing hidden order, which may be associated with a symmetry breaking in the normal state (at T^*) such as, for example, antiferromagnetic fluctuations,[8] current loops in the Cu-O plaquettes,[9] or one-dimensional (1D) stripes.[10] For instance, in the current-loop model, time-reversal symmetry, and inversion symmetry are broken below T^*.[9,11,12] This picture is supported by recent polarized neutron scattering experiments.[13] On the other hand, Moshchalkov *et al.* relate the existence of the pseudogap to the formation of 1D stripes (first proposed by Zaanen and Gunnarsson[10]) below T^*, leading to translational symmetry breaking.[14,15] This is supported by the fitting of the zero-field resistivity—in the metallic part of the phase diagram—of LSCO thin films by a universal law $\rho(T)=\rho_0+CT\exp(-\Delta/T)$, where only Δ and ρ_0 depend on the doping level. (Δ extracted from this fit varies with doping, as expected for the pseudogap, and coincides with NMR data.)

In order to get a better insight into physics below T^*, superconducting fluctuations are of key interest. If precursor pairing occurs, i.e., if the same type of pairs which get bound at T^* do condense at T_C, then Gaussian Ginzburg-Landau fluctuations as calculated by Aslamasov and Larkin[16] are not to be expected at T_C, since the amplitude of the wave function is already defined below T^*, and only phase fluctuations are expected. The only model available to date for these phase fluctuations is the Kosterlitz-Thouless model, in which pairs of vortex-antivortex debind above T_C. These vortices thus become dissipative and ultimately, the order parameter goes to zero at T^*, which is a fluctuation-corrected BCS critical temperature (T_C^0 in the model). This model [namely, a two-dimensional (2D) *XY* model] was proposed by Kosterlitz and Thouless[17] for superfluid helium and applied to 2D type II superconductors by Halperin and Nelson.[18] In the dirty limit approximation, these phase fluctuations should lead to the following expression for the conductivity:[18]

$$\Delta\sigma = 0.37b^{-1}\sigma_N^{squ}\sinh^2[(b\tau_C/\tau)^{1/2}], \qquad (1)$$

where σ_N^{squ} is the normal state conductivity per square, b is a dimensionless parameter of order unity, $\tau=\frac{T-T_C}{T_C}$, and $\tau_C=\frac{T^*-T_C}{T_C}$. σ_N^{squ} and τ_C are not independent and related within the dirty limit approximation through $\tau_C=0.17e^2/(\hbar\sigma_N^{squ})$. In any case (including the clean limit), $\Delta\sigma$ should vary as $\sigma_N^{squ}e^2[\tau_c/\tau]^{1/2}$ in the vicinity of T_C.

However, all measurements of the conductivity due to fluctuations in YBCO or BSCCO at optimal doping seem to be in favor of conventional either 2D or three-dimensional (3D) Aslamasov-Larkin (AL) fluctuations.[19–21,35] This seems to rule out precursor pairing as being responsible for the superconducting transition at least at optimal doping.

In the underdoped regime of the (T,x) phase diagram, the problem which arises is the choice to be made for the resistivity in the normal state. Previous analyses have been made upon the assumption that the resistivity in the normal state remains linear in T for slightly underdoped compounds, as long as no charge carrier localization is present.[21–24,36] This analysis had allowed us to evidence both an Aslamasov-Larkin regime in YBCO thin films and a high-temperature power-law conductivity decrease[21] equivalent to a high-energy cutoff[25] whose energy increases with underdoping. A total energy cutoff had also been introduced by other groups.[26–28]

For small values of ϵ, the measured divergence of $\Delta\sigma$ is not expected to depend on the exact variation of σ_N, however, for larger values of ϵ, the choice made for the normal state becomes relevant, in particular, when studying the power-law decrease of $\Delta\sigma$. As a matter of fact, in the underdoped $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ analyses, the normal state resistivity could only be hypothesized since T_C is too high to be suppressed by the magnetic fields typically available in the laboratory. For strongly underdoped cuprates, it is known that this resistivity is no more linear in T and rather governed by some localization effects, whose nature is still under debate. The critical doping separating insulating from metallic states is found to vary from compound to compound.[29] Therefore, the observed power law for the high-temperature variation of the paraconductivity could be questioned in relation to the choice made for the normal state resistivity.

In order to address the behavior of the fluctuations in the pseudogap regime without any assumption for the normal state, we report here high-field and zero-field measurements of the resistivity of two underdoped $La_{2-x}Sr_xCuO_4$ thin films for $x=0.08$ and $x=0.09$. This material is interesting for two reasons: firstly, because of its superconducting 2D character and, secondly, because of its relatively low T_C allowing the complete suppression of superconductivity by using pulsed fields.[30] Remarkably enough, in two dimensions, the contribution to the conductivity of the Gaussian Aslamasov-Larkin fluctuations—or, more precisely here, of the Lawrence-Doniach fluctuations[31]—is universal and depends only on T, usually expressed as a function of $\epsilon=\ln\left(\frac{T}{T_C}\right)$ in a BCS framework, and sometimes as a function of τ (Ginzburg-Landau formalism),

$$\Delta\sigma = \frac{e^2}{16\hbar d\epsilon} \simeq \frac{e^2}{16\hbar d\tau}. \quad (2)$$

Once T_C is known, the only remaining parameter is d, the spacing between the CuO planes, which is well known from the crystallographic characterization. As opposed to the 3D AL case where the paraconductivity depends on the zero temperature c-axis coherence length, for the 2D case, no free parameters are left. This makes the observation of a 2D AL paraconductivity highly irrefutable. On the other hand, measurements under high magnetic field (50 T) allow us to determine precisely the normal state conductivity in order to subtract it from the measured conductivity.

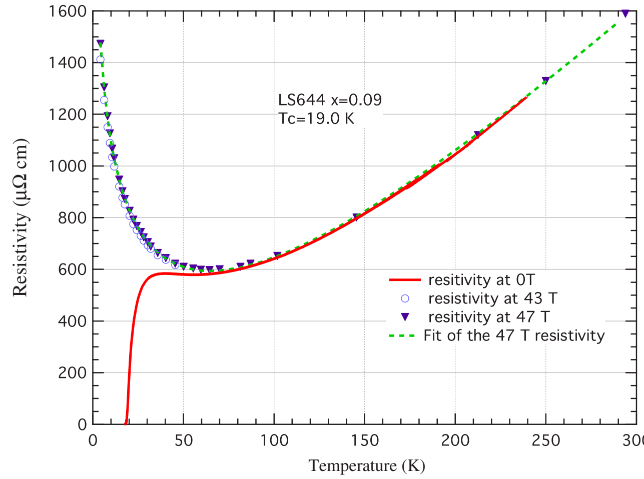

FIG. 1. (Color online) ab-plane resistivity as a function of temperature of the LSCO thin film under high magnetic field. The marine triangles are the data at 47 T; the blue circles are the data at 43 T and the red line is the data at 0 T. The green (dashed) line is an interpolation of the data at 47 T, of the form $\rho[\mu\Omega\ \mathrm{cm}]=490.3\ \ln(80.3/\mathrm{T[K]})+7.54\ \mathrm{T[K]}$.

II. MEASUREMENTS

The as-grown $La_{2-x}Sr_xCuO_4$ films were prepared by dc magnetron sputtering from stoichiometric targets at K.U. Leuven.[32] The transport measurements were carried out at the K.U. Leuven high field facility. The reported data were obtained on thin epitaxial films of typical thickness of a few hundred nanometers, with a patterned strip ($1\ \mathrm{mm}\times 100\ \mu\mathrm{m}$) for four-probe measurements. The c-axis oriented film was mounted with $\mu_0 H \| c$, and the current was always in the ab plane ($I\|ab$). The resistivity was measured at zero magnetic field and for various intensities of the pulsed magnetic field of up to 47 T. Figure 1 shows the 0, 43, and 47 T resistivities as a function of temperature of sample LS644 whose Sr content is 0.09 and T_C is 19.0 K, under different intensities of the magnetic field which was applied perpendicularly to the CuO layers. As can be inferred from Fig. 1, the resistivity has almost saturated between 43 and 47 T, which allows us to consider the 47 T state a reasonably good representative of the normal state. $[(\rho_{47\ \mathrm{T}}-\rho_{43\ \mathrm{T}})/\rho_{47\ \mathrm{T}}\simeq 0.002$ at 20 K.] An interpolation of the 47 T resistivity is then used to obtain $\sigma_{47\ \mathrm{T}}=\frac{1}{\rho_{47\ \mathrm{T}}}$, and the paraconductivity is calculated as $\Delta\sigma=\sigma_{0\ \mathrm{T}}-\sigma_{47\ \mathrm{T}}$. The 47 T resistivity of LS644 can actually be fitted with the function $\rho=\rho_1\log\left(\frac{T_0}{T}\right)-aT$, where $\rho_1=490.3\ \mu\Omega\ \mathrm{cm}$, $T_0=80.3$ K, and $a=7.54\ \mu\Omega\ \mathrm{cm\ K}^{-1}$, which was used for the interpolation (see the dashed line in Fig. 1). Such a $\log(T)$ behavior was already observed by Ando *et al.*[33]

$\Delta\sigma$ is then plotted as a function of ϵ on a log-log scale together with the 2D AL prediction, taking for the spacing between the CuO planes $d=0.66$ nm (Fig. 2). The agreement is quite good from $\epsilon=0.02$ to $\epsilon=0.2$, exactly the same range in ϵ where this regime was found in optimally doped $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+d}$ samples.[20] Although this range is rather narrow, it is worth noticing that, without

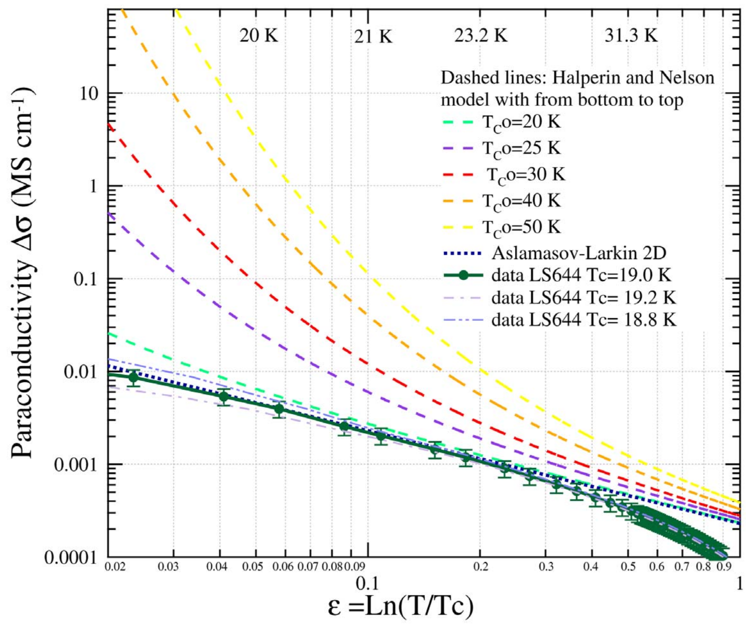

FIG. 2. (Color online) Green markers: Paraconductivity $\Delta\sigma$ as a function of the reduced temperature $\epsilon=\log\left(\frac{T}{T_C}\right)$ for sample LS644, with $T_C=19.0$ K. The error bars are due to uncertainty in the sample thickness and magneto resistance of the normal state. The data are also plotted for $T_C=18.8$ K (dash-dot-dots) and $T_C=19.2$ K (dash-dots). Marine blue dotted line: 2D AL model with $d=0.66$ nm. The dashed lines are for the Halperin-Nelson model (Ref. 18) with different values of T_C^0. (From bottom to top, $T_C^0=20$, 25, 30, 40, and 50 K.)

any adjustable parameter (except T_C but this parameter is hardly adjustable[37]), both the slope and the amplitude of $\Delta\sigma$ match the AL 2D predictions within the error bars. These are due to the uncertainties in the sample dimensions, which give systematic error, and to the small residual magnetoresistance of the normal state. The effect of slightly adjusting the values of T_C is also shown on Fig. 2.

On the same figure, the Halperin-Nelson prediction is plotted for $T_C^0=50$, 40, 30, 25, and 20 K. A clean limit calculation would give[18] $\tau_C\sim 0.0015$ assuming a metallic electron density. In order to achieve a value of τ_C of the order of 0.1 leading to a $T_C^0\sim 21$ K, one would require the electron density to be reduced by a factor of 10^3 with respect to the metallic electron density. In the dirty limit, however,[34] the expected T_C^0 deduced from the value of σ_N should be about 29 K, which is not consistent with the observations (see Fig. 3). In any case, the exponential variation of $\Delta\sigma$ expected in the vicinity of T_C in a phase fluctuation model is not observed, and an upper value for T_C^0 of 20 K can be extracted, much lower than the pseudogap temperature.

At higher temperatures, the above-mentioned steeper decrease of the paraconductivity is observed, as can be seen in Fig. 3, where $\Delta\sigma$ is plotted as a function of T. A power law in T behavior is also evidenced here between 24 and 80 K. The exponent α is found to be equal to 3.0, which gives $\epsilon_0 = 1/\alpha = 0.33$. Another sample with $x=0.08$ was measured at the LNCMP-Toulouse high field facility by one of us under magnetic field of up to 50 T. The same high field resistivity interpolation was used to determine the normal state; the superconductive fluctuations were measured and also found to be consistent with 2D AL fluctuations. At higher temperatures, the same power-law decrease of the paraconductivity in $T^{-\alpha}$ was observed with $\alpha\approx 3$ (see the inset in Fig. 3).

The quantitative observation of a 2D AL regime for the paraconductivity of a very underdoped LSCO compound is rather surprising. The Fermi surface in the normal state of

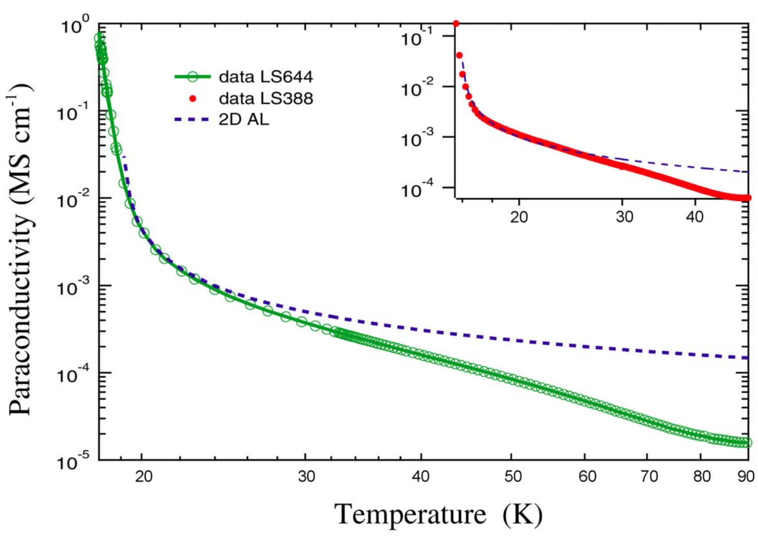

FIG. 3. (Color online) Paraconductivity $\Delta\sigma$ as a function of the temperature. Green circles, LS644 ($x=0.09$); red dots (inset), LS388 ($x=0.08$). After the 2D AL regime (blue dashed line), a linear regime is observed, which corresponds to a power law in $T^{-\alpha}$ with the exponent $\alpha\approx 3$.

this material is suppressed by the opening of a pseudogap, which, for that level of doping, leaves just a Fermi arc around the nodal directions. The fact that, in that framework, AL predictions remain valid is remarkable, although this model does not depend explicitly on the density of states at the Fermi energy.

III. CONCLUSION

Careful measurements of the resistivity of underdoped thin films of LSCO at zero magnetic field and under magnetic field of up to 50 T have allowed us to extract the paraconductivity without any assumption about the normal state behavior. The observed saturation of the resistivity with the magnetic field is an indication that the magnetoresistance of the normal state is negligible. With no adjustable parameter, the paraconductivity quantitatively shows a two-dimensional Aslamazov-Larkin regime near T_C and a power-law dependence at higher temperatures (typically up to 80 K). This behavior is in contradiction with what should be expected for preformed superconducting pairs, where a 2D Kosterlitz-Thouless behavior should be expected above T_C with exponential variations in T. Therefore, these results suggest that, quite surprisingly, the validity of the 2D AL regime of fluctuations survives the opening of a well developed pseudogap in the Fermi surface. Although we do not have hitherto a complete understanding of the mechanism which dampens the fluctuations at high temperature, these results may indicate a competing process between rather conventional superconducting fluctuations and the mechanism responsible for the pseudogap.

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[35] In any case, no Maki-Thomson contribution was found or expected due to the gap anisotropy.
[36] For the most underdoped compounds, a variable range hopping resistivity was added to this linear resistivity.
[37] T_C has been taken to be equal to 19.0 K, which is between the temperature at the inflection point (19.2 K) and the temperature of intersection between the tangent at the inflection point and the temperature axis (18.8 K), which are the two extrema allowed for T_C.