Paraconductivity at high reduced temperatures in $YBa_2Cu_3O_{7-\delta}$ superconductors

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By using high quality single crystals and epitaxial thin films, the in-plane paraconductivity in almost optimally doped $YBa_2Cu_3O_{7-\delta}$, with $T_{c0}\gtrsim 92$ K, was determined well inside the so-called short-wavelength fluctuation regime, which corresponds to reduced temperatures, $\epsilon\equiv\ln(T/T_{c0})$, above typically $\epsilon=0.1$. It is then shown that these data may be explained in terms of the Gaussian-Ginzburg-Landau approach for bilayered superconductors by introducing a total energy cutoff, instead of the momentum cutoff approximation always used until now. These results seem to confirm the absence of appreciable pseudogap effects on the in-plane resistivity in optimally doped $YBa_2Cu_3O_{7-\delta}$ superconductors.

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I. INTRODUCTION

Thermal fluctuations of Cooper pairs and of magnetic vortices is one of the interesting aspects of the physics of the high temperature cuprate superconductors (HTSC).[1] In the case of the thermal fluctuations of Cooper pairs above the superconducting transition temperature with zero applied magnetic field, T_{c0}, one of the problems still open at present is the behavior of these fluctuations in the high-reduced-temperature region, i.e., at reduced temperatures $\epsilon\equiv\ln(T/T_{c0})$ higher than typically 0.1. In particular, it was early observed that for $\epsilon\gtrsim 0.1$ the fluctuation effects on the electrical conductivity measured parallel to the superconducting CuO_2 layers [the in-plane paraconductivity, $\Delta\sigma_{ab}(\epsilon)$] in different HTSC compounds strongly disagree with the conventional mean-field-like behavior for layered superconductors which may be easily calculated using the Gaussian-Ginzburg-Landau (GGL) approach.[2–6] This contrasts with the $\Delta\sigma_{ab}(\epsilon)$ results for $10^{-2}\lesssim\epsilon\lesssim 10^{-1}$, which may be understood at a quantitative level (both in amplitude and ϵ behavior) on the grounds of the GGL approach for multilayered superconductors.[3–10]

A similar failure of the mean-field-like approaches to explain the paraconductivity in the high-reduced-temperature region was already observed by Johnson, Tsuei, and Chaudhari[11] in some low temperature superconductors (LTSC) and it was attributed to the fact that at these high-reduced-temperatures the GGL theory strongly overestimates the statistical weight of the fluctuations with characteristic lengths of the order of $\xi(0)$, the superconducting coherence length amplitude at $T=0$ K. These short wavelength fluctuations break down the "slow variation condition" for the superconducting order parameter, a central hypothesis of the GGL approach.[12] In fact, this difficulty affects any Landau-type theory of the thermal fluctuations around a phase transition, as it was noticed for the first time by Levanyuk in the general case[13] and then, in the case of the superconducting transition, by Schmid[14] and by Gollub and co-workers.[15] These early results already suggested that the paraconductivity calculated on the grounds of the GGL approaches could be extended to the short wavelength region by introducing a momentum cutoff in the fluctuation spectrum, i.e., by imposing the condition[11,14,15]

$$k^2<c\xi^{-2}(0), \tag{1}$$

where k is the momentum (in units of the reduced Planck constant, $\hbar$) of each fluctuating mode, $\Psi_{\mathbf{k}}$, and c is a constant (temperature independent) cutoff amplitude close to 1. Such a procedure has already somewhat mitigated the disagreement between the theoretical $\Delta\sigma(\epsilon)$ and the experimental results around $\epsilon\simeq 0.1$, but without eliminating the differences, which above $\epsilon\sim 0.2$ remain very important in both LTSC (Ref. 11) and HTSC.[2,5,6] Although in the last years there has been other theoretical attempts to understand the high-reduced-temperature behavior of $\Delta\sigma_{ab}(\epsilon)$ in HTSC,[16] until now this problem, which concerns both the phenomenological and the microscopic aspects of the fluctuating Cooper pairs in these materials,[1,17] remains completely unsolved.

As a further attempt to understand the behavior of the thermal fluctuations of Cooper pairs in the high-reduced-temperature region ($\epsilon\gtrsim 0.1$) in HTSC, in this paper we first present detailed measurements of the in-plane paraconductivity in almost optimally doped $YBa_2Cu_3O_{7-\delta}$(Y-123) single crystals and epitaxial thin films in the ϵ region bounded by $10^{-2}\lesssim\epsilon\lesssim 1$, which covers more than three orders of magnitude in paraconductivity amplitude, and which allows us to deeply penetrate in the short wavelength region for the thermal fluctuations. We calculate then $\Delta\sigma_{ab}(\epsilon)$ on the grounds of the bilayered GGL approximation but by taking into account the short wavelength fluctuations through two different cutoff conditions: The conventional momentum cutoff [Eq. (1)] and, for the first time, by using a cutoff in the *total energy* of the fluctuating modes (in units of $\hbar^2/2m^*$, where m^* is the effective mass of the Cooper pairs),

$$[k^2+\xi^{-2}(\epsilon)]<c\xi^{-2}(0). \qquad (2)$$

This last condition eliminates the most energetic fluctuating modes and not only those with short wavelengths [which are the only ones suppressed by Eq. (1)]. A total energy cutoff was already suggested, on the basis of a microscopic approach, by Patton and co-workers[18] and by Nam[19] when studying the short-wavelength regime in the fluctuation-induced-diamagnetism at high applied magnetic fields in LTSC. However, such a cutoff condition has been never used until now to analyze the paraconductivity in LTSC or in HTSC in the high-reduced-temperature region. Its adequacy can be easily inferred on the grounds of the GGL approach by just taking into account that the probability of each fluctuating mode is controlled by its total energy $[k^2+\xi^{-2}(\epsilon)]$ and not only to its momentum.[12] Therefore, the momentum cutoff given by Eq. (1) considers fluctuation modes at high temperatures which, due to the shrinking of the coherence length, are less probable than others which are eliminated by this cutoff criterion close to T_{c0}. This is why the use of a momentum cutoff in the GGL approach, although it may be a reasonable approximation near T_{c0}, leads to an overestimation of the fluctuation effects at high temperatures, when $\xi(\epsilon)$ becomes of the order of $\xi(0)$. We will see in this paper that the use of the total energy cutoff given by Eq. (2) corrects this failure.

II. EXPERIMENTAL DETAILS AND RESULTS

One of the main motivations of our choice of the almost optimally doped Y-123 single crystals and epitaxial thin films, with $T_{c0}\gtrsim 92$ K, to determine $\Delta\sigma_{ab}(\epsilon)$ in the high-reduced-temperature region was the common assumption of the absence of important effects on the normal in-plane resistivity, $\rho_{ab}(T)$, associated with the normal state pseudogap in this samples.[20] This will avoid the possible entanglement between both type of intrinsic effects, those associated with the pseudogap and with the thermal fluctuations, which could make difficult their separation, mainly in the high-reduced-temperature region. In fact, we will see here that our present results seem to confirm the absence of appreciable pseudogap effects on $\rho_{ab}(T)$ in these optimally doped samples: when properly calculated, the thermal fluctuations alone provide a quantitative explanation of the observed deviations above T_{c0} of the linearity of the normal resistivity. But, in addition, these optimally doped samples also present two important experimental advantages: First, at present it is quite easy to grow high quality samples of this cuprate family, which probably are those that present the best stoichiometric and structural quality of all the available samples of any HTSC system. Second, it is now well established[2–10,21] that $\rho_{ab}(T)$ of the almost optimally doped Y-123 samples presents at a quantitative level a linear temperature dependence for $\epsilon\gtrsim 1$, i.e., for $T\gtrsim 200$ K and up to at least 300 K. We will see here below that these characteristics are of crucial importance for a reliable extraction of the paraconductivity in the high-reduced-temperature region.

The preparation and characterization procedures of the different Y-123 single crystals and epitaxial thin films used here and also the experimental setup used to measure their in-plane resistivity as a function of the temperature have been reported in detail elsewhere.[7,22] The general characteristics of these samples, including their in-plane resistivity (see below), are similar to those of the best optimally doped Y-123 samples studied until now.[3–10] The main differences with previous paraconductivity analyses in optimally doped Y-123 samples concern the estimation of the so-called bare or background resistivity, $\rho_{abB}(\epsilon)$, used to extract the in-plane paraconductivity through the conventional expression $\Delta\sigma_{ab}(\epsilon)\equiv\rho_{ab}^{-1}(\epsilon)-\rho_{abB}^{-1}(\epsilon)$.[2–10] This background resistivity may be seen as the resistivity that the samples would have in absence of thermal fluctuations effects and it may be estimated by extrapolating through the transition the $\rho_{ab}(T)$ data obtained well above T_{c0}, in a temperature region where these fluctuation effects may be negligible. In most of the previous works, including those that have analyzed before the paraconductivity in the high-reduced-temperature region, $\rho_{abB}(\epsilon)$ was estimated by extrapolating the normal resistivity data above typically 150 K.[2–10] Such a choice of the background region does not appreciably affect $\Delta\sigma_{ab}(\epsilon)$ for temperatures relatively close to T_{c0} (for $\epsilon<0.1$) but its influence may be important in the high-reduced-temperature region (for $\epsilon>0.1$). In particular, this choice arbitrarily imposes $\Delta\sigma_{ab}(\epsilon)=0$ for $\epsilon\gtrsim 0.5$. In our present work we attempt to avoid these shortcomings by locating the background region as far as possible from T_{c0}, but imposing simultaneously that such a background must reproduce at a quantitative level the already very well established in-plane paraconductivity results in Y-123 samples in the ϵ region bounded by $10^{-2}\leq\epsilon\leq 10^{-1}$.[2–10] This last condition provides a convenient check for the upper limit of the temperature distance between the analyzed data points and the background fitting region, the dispersion due to the background uncertainties being strongly amplified when this temperature distance increases. Our systematic analyses of different background regions in different samples let us to propose as background region the one to between 225 K (which corresponds to $\epsilon\simeq 0.9$) and 275 K. Such a procedure is adequate only in the case of high quality optimally doped Y-123 samples having at a quantitative level a linear normal state resistivity in this temperature region. Therefore, among all the different samples we have studied, we have finally selected those that present a linear $\rho_{ab}(T)$ above 225 K, with a rms of 0.1% or less, which extrapolates to zero resistivity at $T=0$ K well to within ± 10 $\mu\Omega$ cm and with $0.5\,\mu\Omega\,\mathrm{cm\,K^{-1}}\leq d\rho_{ab}/dT\leq 1\,\mu\Omega\,\mathrm{cm\,K^{-1}}$. We have checked that for these samples the $\Delta\sigma_{ab}(\epsilon)$ data are very stable to small changes of extension and localization of the fitting region. For instance, by changing it from 225–275 K to 200–250 K we found that $\Delta\sigma_{ab}(\epsilon)$ change less than 10% for $\epsilon<0.1$ and less than 50% for $0.1<\epsilon<0.5$ (see below).

An overview of the in-plane resistivity as a function of the temperature for three of our samples having the above indicated general characteristics is presented in Fig. 1(a). The solid lines are the corresponding resistivity backgrounds,

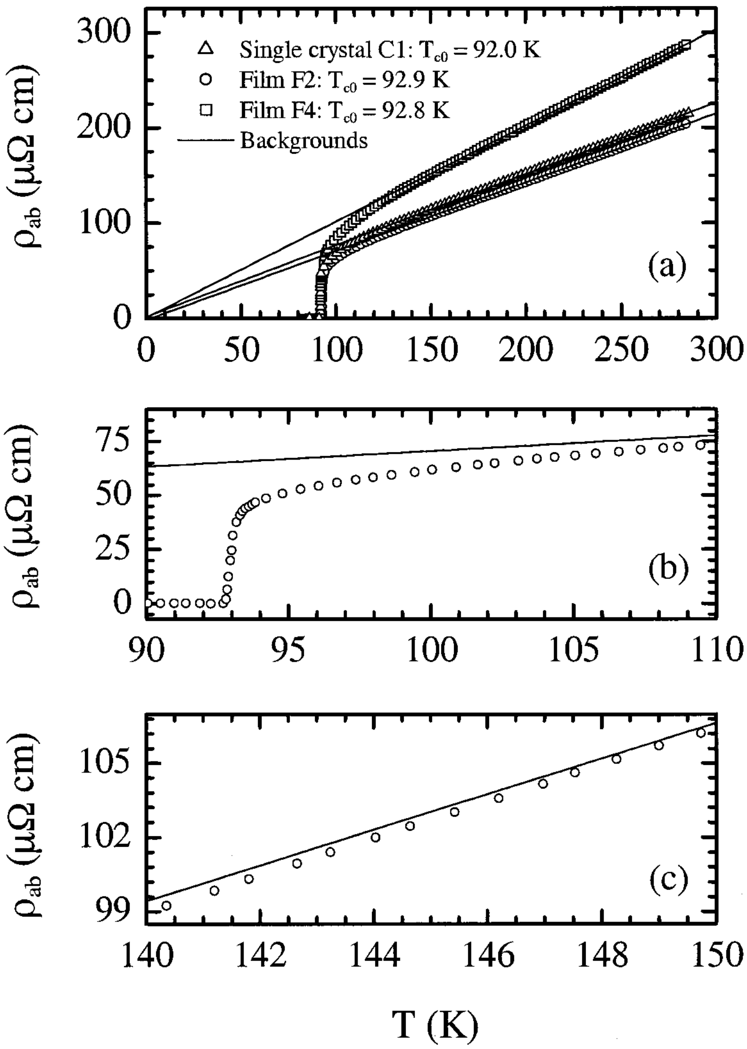

FIG. 1. Three examples of the resistivity versus temperature curves of the almost optimally doped $YBa_2Cu_3O_{7-\delta}$ samples studied here. The solid lines correspond to the so-called background resistivity and they were obtained by extrapolating the linear resistivity measured above 225 K. For clearness, we have plotted in this figure only 2% of the measured data. The scoops in (b) and (c) correspond to the epitaxial film noted $F2$.

which correspond then to the extrapolation through the transition of their normal resistivity obtained in the region 225 K$\leqslant T \leqslant$275 K. Two scoops of these results for temperatures around T_{c0} and well above the transition are shown in Fig. 1(b) and, respectively, Fig. 1(c). These data correspond to the $F2$ film.

The in-plane paraconductivity of the three samples selected above is shown in Fig. 2. The shadowed region in this

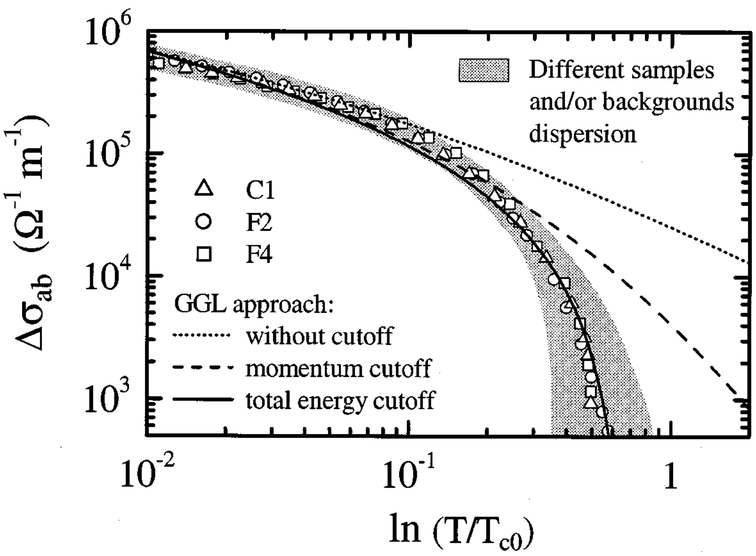

FIG. 2. Comparison of the in-plane paraconductivity measured in different optimally doped Y-123 samples with the GGL predictions under different cutoff conditions. In spite of the uncertainties associated with the background, these results clearly illustrate the improvement of the GGL approach when a total energy cutoff condition is used.

figure corresponds to the $\Delta\sigma_{ab}(\epsilon)$ data obtained in the other samples we have studied in this work. This region also covers the $\Delta\sigma_{ab}(\epsilon)$ data obtained by other groups in high quality optimally doped Y-123 single crystals,[8,10] and the always existent uncertainty in the background subtraction. In fact, in some of these samples the uncertainties due to the extrapolation of the normal resistivity above 225 K must be mitigated by just in this case *imposing* that close to T_{c0} (let us say, $\epsilon=5\times10^{-2}$) the corresponding paraconductivity must agree with the one obtained by using as a background the normal resistivity extrapolated above 150 K. Note that the data in Fig. 2 extend over almost two orders of magnitude in reduced temperature, which correspond to more than three orders of magnitude in $\Delta\sigma_{ab}(\epsilon)$ amplitude. As we are interested in studying the so-called mean-field region, were the GGL approaches are expected to apply, we have only represented our data for $\epsilon\gtrsim10^{-2}$. This is because for $\epsilon\lesssim10^{-2}$ it appears a different $\Delta\sigma_{ab}(\epsilon)$ behavior which may be attributed to the penetration in the so-called full-critical region.[4,7–10] Note finally that, as it can be seen in Fig. 2, in the high-reduced-temperature region ($\epsilon\gtrsim0.1$) the relative experimental dispersion strongly increases, mainly due to the background uncertainties, and above $\epsilon\sim0.3$ becomes of the order or even bigger than 100%. However, we will see below that in this temperature region the differences among the various theoretical predictions remain bigger than these uncertainties.

III. PARACONDUCTIVITY UNDER DIFFERENT CUTOFF CONDITIONS

A. Theory

The paraconductivity under different cutoff conditions may be calculated on the grounds of the phenomenological GGL approach by using the relationship between $\Delta\sigma_{ab}(\epsilon)$ and the momentum of the fluctuating modes. Such a relationship may in turn be easily obtained following the same procedure proposed in Ref. 9 to calculate $\Delta\sigma_{ab}(\epsilon)$ without a cutoff. In the case of a *single layered* superconductor, the resulting expression is

$$\Delta\sigma_{ab}(\epsilon)=\frac{e^2\xi_{ab}^4(0)}{8\pi\hbar}\int dk_z\int dk_{xy}\times\frac{k_{xy}^3}{\{\epsilon+B_{\rm LD}[1-\cos(k_zs)]/2+\xi_{ab}^2(0)k_{xy}^2\}^3},\tag{3}$$

where k_z and k_{xy} are, respectively, the z momentum and the modulus of the in-plane momentum of the fluctuation modes, e is the electron charge, $B_{\rm LD}\equiv(2\xi_c(0)/s)^2$ is the so-called Lawrence-Doniach (LD) parameter which controls the fluctuation dimensionality, s is the superconducting layers periodicity length, and $\xi_{ab}(0)$ and $\xi_c(0)$ are, respectively, the in-plane and the out-of-plane superconducting coherence length amplitudes at $T=0$ K. Let us stress that in applying Eq. (3) to the *bilayered* Y-123 compound the effective periodicity length must be equal to one half the crystallographic periodicity of the CuO_2 layers, i.e., in our case $s=11.7/2$ Å $\simeq5.9$ Å. This approximation, that is going to be used through all this paper, is indeed adequate to bilayered superconductors with a similar Josephson coupling strength between the adjacent CuO_2 layers which, as it is now well established, is the case of Y-123.[4,9]

Equation (3) is general and the in-plane paraconductivity for any cutoff criterion may be obtained by simply imposing the corresponding upper limits on the k integrals. In the case of the in-plane paraconductivity predicted in single layered superconductors without any cutoff, it is only necessary to take into account that the out-of-plane spectrum of the fluctuations is limited by the layered structure through $|k_z|\leqslant\pi/s$, whereas the integral on k_{xy} should be carried out up to the infinity. This leads to

$$\Delta\sigma_{ab}(\epsilon)=\frac{e^2}{16\hbar s}\frac{1}{\epsilon}\left(1+\frac{B_{\rm LD}}{\epsilon}\right)^{-1/2},\tag{4}$$

which is the well-known LD expression.[4]

To calculate $\Delta\sigma_{ab}(\epsilon)$ under a momentum cutoff, we note first that since the z spectrum of the fluctuations is already modulated through $-\pi/s\leqslant k_z\leqslant\pi/s$, the inclusion of a momentum cutoff in this direction is not necessary. For Y-123, this is a correct approach because the effective periodicity is $s=5.9$ Å, whereas $\xi_c(0)\simeq1.1$ Å and, therefore, the condition $|k_z|\leqslant\pi/s$ is stronger than $k_z^2<c\xi_c^{-2}(0)$ (if $c\simeq1$, see below). So, Eq. (1) becomes $k_{xy}^2<c\xi_{ab}^{-2}(0)$. The in-plane paraconductivity under the momentum cutoff criterion, $\Delta\sigma_{ab}(\epsilon,c)_M$, is then found to be

$$\Delta\sigma_{ab}(\epsilon,c)_M=\frac{e^2}{16\hbar s}\left\{\frac{1}{\epsilon}\left(1+\frac{B_{\rm LD}}{\epsilon}\right)^{-1/2}-\frac{c(c+\epsilon+B_{\rm LD}/2)}{[(c+\epsilon+B_{\rm LD})(c+\epsilon)]^{3/2}}-\frac{1}{\epsilon+c}\left(1+\frac{B_{\rm LD}}{\epsilon+c}\right)^{-1/2}\right\}.\tag{5}$$

This expression has two interesting asymptotic limits: the conventional LD in-plane para-conductivity, Eq. (4), which is recovered by imposing $\epsilon\ll c$, and the 2D limit of the paraconductivity under a momentum cutoff which may be obtained by just imposing $B_{\rm LD}\ll\epsilon$. In this last case we obtain

$$\Delta\sigma_{ab}^{\rm 2D}(\epsilon,c)_M=\frac{e^2}{16\hbar s}\left[\frac{1}{\epsilon}-\frac{c}{(c+\epsilon)^2}-\frac{1}{\epsilon+c}\right],\tag{6}$$

which corresponds to the $\Delta\sigma_{ab}(\epsilon,c)_M$ expression first obtained for this 2D limit in Ref. 6. Note that for $\epsilon\gg c$, this expression is proportional to ϵ^{-3}.

To obtain from Eq. (3) the in-plane paraconductivity under a total energy cutoff, $\Delta\sigma_{ab}(\epsilon,c)_E$, we must first note that the total energy of the fluctuation modes is given by[4,9]

$$E(\Psi_{\mathbf{k}})=k_{xy}^2+\xi_{ab}^{-2}(0)[\epsilon+B_{\rm LD}(1-\cos(k_zs))/2].\tag{7}$$

Therefore, the total energy cutoff limits the in-plane momentum of the fluctuations through

$$k_{xy}^2 < [c-\epsilon-B_{\rm LD}(1-\cos(k_z s))/2]\xi_{ab}^{-2}(0), \tag{8}$$

whereas k_z is restricted, as in the case of the momentum cutoff, to the interval $-\pi/s \leqslant k_z \leqslant \pi/s$. By introducing these limits of integration in Eq. (3) we obtain

$$\Delta\sigma_{ab}(\epsilon,c)_E = \frac{e^2}{16\hbar s}\left[\frac{1}{\epsilon}\left(1+\frac{B_{\rm LD}}{\epsilon}\right)^{-1/2} - \frac{2}{c} + \frac{\epsilon + B_{\rm LD}/2}{c^2}\right]. \tag{9}$$

Here again the LD limit [Eq. (4)] can be recovered by simply imposing $\epsilon \ll c$, whereas the 2D limit corresponds to $B_{\rm LD} \ll \epsilon$. This last gives

$$\Delta\sigma_{ba}^{\rm 2D}(\epsilon,c)_E = \frac{e^2}{16\hbar s}\left(\frac{1}{\epsilon} - \frac{2}{c} + \frac{\epsilon}{c^2}\right). \tag{10}$$

For completeness, we also calculate here the $\Delta\sigma(\epsilon,c)$ expressions for bulk isotropic (3D) superconductors under both cutoff conditions. These expressions cannot be obtained by just imposing the 3D condition, $B_{\rm LD} \gg \epsilon$, in Eqs. (5) and (9), because these last equations were calculated by supposing that the inclusion of a cutoff in the z direction is not necessary in layered superconductors. However, this last simplification is not indeed adequate in the 3D case. So, we first use the condition $B_{\rm LD} \gg \epsilon$ in Eq. (3) to obtain[2,6]

$$\Delta\sigma^{\rm 3D}(\epsilon) = \frac{e^2 \xi^4(0)}{6\pi\hbar}\int dk \frac{k^4}{[\epsilon + \xi^2(0)k^2]^3}. \tag{11}$$

The paraconductivity under any cutoff condition may be calculated now by simply imposing in the above equation the corresponding limit in the k integral. Then, we get

$$\Delta\sigma_{ab}^{\rm 3D}(\epsilon) = \frac{e^2}{32\hbar\,\xi(0)}\,\epsilon^{-1/2}, \tag{12}$$

$$\Delta\sigma_{ab}^{\rm 3D}(\epsilon,c)_M = \frac{e^2}{48\pi\hbar\,\xi(0)}\left\{3\left[\frac{\arctan(\sqrt{c/\epsilon})}{\sqrt{\epsilon}} - \frac{\epsilon\sqrt{c}}{(\epsilon+c)^2}\right] - 5\,\frac{c^{3/2}}{(\epsilon+c)^2}\right\}, \tag{13}$$

and

$$\Delta\sigma_{ab}^{\rm 3D}(\epsilon,c)_E = \frac{e^2}{48\pi\hbar\,\xi(0)}\left\{3\left[\frac{\arctan(\sqrt{(c-\epsilon)/\epsilon})}{\sqrt{\epsilon}} - \frac{\epsilon\sqrt{c-\epsilon}}{c^2}\right] - 5\,\frac{(c-\epsilon)^{3/2}}{c^2}\right\}, \tag{14}$$

for, respectively, the 3D paraconductivity without cutoff, with momentum cutoff and with total energy cutoff. Note that Eq. (12) may be recovered from both Eq. (13) and Eq. (14) by simply imposing $\epsilon \ll c$.

Let us finally note that some of the similitudes and differences between $\Delta\sigma_{ab}(\epsilon,c)$ for both cutoff conditions may be easily obtained by just rewriting Eq. (2) as $k^2 < (c-\epsilon)\xi^{-2}(0)$, where we have assumed the mean-field ϵ dependence of the superconducting coherence length, $\xi(\epsilon) = \xi(0)\epsilon^{-1/2}$. We see, in particular, that close to T_{c0}, when $\epsilon \ll c$, both cutoff conditions coincide and they will affect in the same way not only the paraconductivity [as it can be easily checked by comparing Eqs. (5) and (9)] but also the thermal fluctuation effects above T_{c0} on any other observable.[23] The main paraconductivity difference between both cutoff conditions appears when ϵ becomes of the order of c: Whereas under the momentum cutoff condition the paraconductivity amplitude decreases below its value in absence of a cutoff but it does not present any singularity at $\epsilon = c$, it approaches to zero at such a reduced temperature under the total energy cutoff.

B. Comparison with the experimental data

The dotted curve in Fig. 2 corresponds to the best fit of the in-plane paraconductivity predicted by the GGL approach without any cutoff condition [Eq. (4)] to the experimental data measured in sample $F2$ (circles). In comparing Eq. (4) with the measurements the only free parameter is $\xi_c(0)$, which has been determined by fitting Eq. (4) to the data in the region $10^{-2} \lesssim \epsilon \lesssim 10^{-1}$. This leads to $\xi_c(0) \simeq 1.1$ Å. As expected,[2–10] the agreement between Eq. (4) and the experimental data is excellent for $10^{-2} \lesssim \epsilon \lesssim 10^{-1}$ but appreciable differences appear already for $\epsilon > 10^{-1}$. The solid line in this figure corresponds to the best fit of Eq. (9), with $\xi_c(0)$ and c as free parameters, to the experimental data obtained in sample $F2$ in the ϵ region $10^{-2} \leqslant \epsilon \leqslant 5 \times 10^{-1}$. As it can be seen, the agreement is excellent in almost the entire ϵ region and it leads to $\xi_c(0) \simeq 1.0$ Å for sample $F2$ [which is well within the accepted value of $\xi_c(0) = 1.1 \pm 0.1$ Å] (Refs. 3–10) and $c = 0.7$ [which is comparable with the cutoff amplitude we have found in other HTSC by studying the fluctuation induced diamagnetism near T_{c0} (Ref. 23)]. In contrast, the dashed line, which was obtained by using these last values of $\xi_c(0)$ and of c in Eq. (5), appreciably differs from the data when $\epsilon \gtrsim 0.2$. Such a disagreement between the experimental results and $\Delta\sigma_{ab}(\epsilon,c)_M$ cannot be overcome by using other values of $\xi_c(0)$ and c: A lower value of c will mitigate the disagreement in the high-reduced-temperature region but it will then break the agreement for $10^{-2} \lesssim \epsilon \lesssim 10^{-1}$. Analogous results were obtained, with almost the same values of $\xi_c(0)$ and c, in the analyses of the measurements in the samples $F4$ (squares) and $C1$ (triangles). The data dispersion among our different measurements (shadowed region) is mainly due to the uncertainties in the background subtraction and not to $\rho_{ab}(T)$ differences between samples. This dispersion leads to values of c between 0.5 and 1 for optimally doped Y-123 superconductors. Note also that some differences between the theoretical $\Delta\sigma_{ab}(\epsilon,c)_E$ and the data appear around $\epsilon \simeq 8 \times 10^{-2}$. Although they are well inside the dispersion among our different measurements, we believe that these differences are real and that they could be due to the crudeness of our cutoff procedure. In fact, such a disagreement is mitigated in the case of those samples and/or backgrounds which lead to somewhat higher values of c than the used in Fig. 2 (upper part of the shadowed region). However, the data points explicitly analyzed in Fig. 2 represent better the values of $\Delta\sigma_{ab}(\epsilon)$ measured in most of the samples.

Let us finally stress that the above conclusion also applies, at least at a qualitative level, to the $\Delta\sigma(\epsilon)$ measurements of Ref. 11 in bulk amorphous LTSC: By comparing these data with Eqs. (13) and (14) we have found that the best agreement corresponds to the total energy cutoff condition, and it leads to $c\simeq 0.9$. It will be, however, very useful to have new data of the paraconductivity in the high-reduced-temperature region in other LTSC.

IV. CONCLUSIONS

By using high quality single crystals and epitaxial thin films, the in-plane paraconductivity of optimally doped $YBa_2Cu_3O_{7-\delta}$ superconductors was determined at all reduced temperatures above 10^{-2}, including the so-called high-reduced-temperature region (above typically 10^{-1}). It is then shown that these data may be explained in terms of the Gaussian-Ginzburg-Landau approach for bilayered superconductors by introducing a total energy cutoff in the spectrum of the fluctuations, instead of the momentum cutoff approximation always used until now. In some extent, this total energy cutoff takes into account the energy contribution associated with the localization of the two carriers in $\xi(\epsilon)$, the characteristic Cooper pair size. These results probably solve then, at a phenomenological level, the long standing problem addressed in the Introduction of this paper. They may also have implications on other general aspects of the HTSC physics. In particular, these results seem to confirm the absence of appreciable pseudogap effects on $\rho_{ab}(T)$ in these optimally doped samples: when properly calculated, the thermal fluctuations alone provide a quantitative explanation, even well above T_{c0}, of the observed deviations of the linearity of the normal resistivity. These results also suggest a similar mean-field-like behavior (with different dimensionality but with, apparently, a comparable cutoff strength) for the fluctuating Cooper pairs in both the LTSC and these HTSC, whose implications on the descriptions of the superconducting transition will deserve further analyses. In fact, our results suggest that also in the normal state the smaller possible size of a fluctuating Cooper pair is of the order of $\xi(0)$. The paraconductivity expressions under a total energy cutoff provide a useful tool to examine the behavior of the fluctuating Cooper pairs in all the normal region not too close to T_{c0} in LTSC and in other HTSC systems and with different doping. The implications of the total energy cutoff on the behavior of other observables (in particular, the fluctuation induced diamagnetism) in the high-reduced-temperature region also deserve further analyses.

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