Universal behavior of the in-plane paraconductivity of cuprate superconductors in the short-wavelength fluctuation regime

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The in-plane paraconductivity was measured in the so-called high reduced-temperature region [for $\varepsilon \equiv \ln(T/T_C)$ well above 0.1] in high-quality single crystals or epitaxial thin films of highly anisotropic cuprate superconductors with different number of superconducting layers per periodicity length. Although the high-ε behavior of the paraconductivity cannot be described in terms of a critical exponent in ε, in all the cases we observe the same type of rapid fall-off at the same (well within the experimental uncertainties) reduced-temperature $\varepsilon^C \simeq 0.7$. These results may be explained in terms of the multilayered Gaussian-Ginzburg-Landau approach by taking into account that due to the uncertainty principle also above T_C the superconducting coherence length cannot be appreciably smaller than at $T=0$ K.

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The behavior of the thermal fluctuations well above the superconducting transition temperature T_C is a long standing open problem which interest has been considerably enhanced by the discovery of the high-temperature cuprate superconductors (HTSC's).[1–3] In such a high reduced-temperature region, typically for $\varepsilon \equiv \ln(T/T_C) \gtrsim 0.1$, the thermal fluctuations may be deeply affected by the so-called short-wavelength fluctuation effects, that appear when their characteristic wavelengths became of the order of the superconducting coherence length amplitude (extrapolated to $T=0$ K) $\xi(0)$. In addition to their intrinsic interest, the thermally activated Cooper pairs well inside the normal state may directly concern in HTSC's the formation of the superconducting state itself.[4]

Recently, we have proposed that the short-wavelength superconducting fluctuation regime may be explained on the grounds of the Gaussian-Ginzburg-Landau (GGL) approach by introducing a total-energy cutoff,[5,6] instead of the momentum cutoff always used previously in low-temperature metallic superconductors (LTSC's) (Ref. 7) and HTSC's.[8–10] This total-energy cutoff takes into account a localization-energy contribution associated with the shrinkage of the fluctuations when the reduced-temperature increases.[5,6,11] In the case of the paraconductivity, the adequacy of this proposal was until now checked only in optimally-doped $YBa_2Cu_3O_{7-\delta}$ (Y-123).[5] The central aim of the present paper is to probe the generality of these ideas by studying other HTSC's with higher anisotropy (what will affect the fluctuations' dimensionality) and with different number of superconducting CuO_2 layers per periodicity length (what will affect the fluctuations' amplitude). For that, we have measured the in-plane paraconductivity $\Delta\sigma_{ab}(\varepsilon)$ in high-quality samples of three families of very anisotropic HTSC: the optimally doped trilayered $Tl_2Ba_2Ca_2Cu_3O_{10}$ (Tl-2223) and bilayered $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212), and the underdoped single-layered $La_{1.9}Sr_{0.1}CuO_4$ (LaSCO/0.1). Our measurements will cover the reduced-temperature region $10^{-2} \lesssim \varepsilon \lesssim 1$, deeply penetrating therefore in the short-wavelength fluctuation regime. Then, we will analyze these results on the grounds of the GGL approach by using both the conventional momentum cutoff and the total-energy cutoff. Our results confirm the adequacy of the latter to explain $\Delta\sigma_{ab}(\varepsilon)$ in these different HTSC's, and also show that in all of them the value of the total-energy cutoff parameter is, well within our experimental uncertainties, the same as for the less anisotropic Y-123. This, in turn, supports a universal origin for the total-energy cutoff, in agreement then with the ideas presented in Refs. 5, 6, and 11 which, as noted before, relate it to the shrinkage at high reduced-temperatures of the superconducting wave function. In addition to the above, our data in the underdoped LaSCO/0.1 also indicate that its normal-state pseudogap does not appreciably affect the amplitude and ε dependence of $\Delta\sigma_{ab}(\varepsilon)$ even in the high-ε region. This contrasts with the proposals linking the opening of such a pseudogap with Cooper pairs preformation.[4]

The high-quality samples studied here are a Tl-2223 single crystal, a Bi-2212 single crystal, and a LaSCO/0.1 epitaxial thin film. Their preparation and characterization procedures have been reported elsewhere.[12–14] The general characteristics of these superconductors, including their T_C and resistivity transition widths, compare favorably with those of the best samples of these compounds studied until now (see below).[12–14] The experimental setup used to measure their in-plane resistivity as a function of temperature is similar to the one we used in other experiments in the low-ε region. This experimental setup and also the results obtained in such low-ε region have been already described in detail in Refs. 15 and 16.

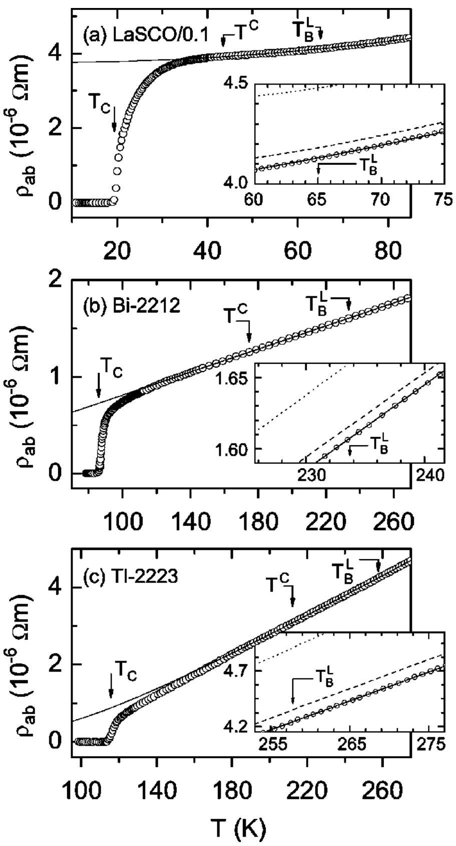

FIG. 1. Main figures: In-plane resistivity versus temperature of the three highly anisotropic HTSC's studied here, and nonfluctuating backgrounds (solid lines) obtained by extrapolation from temperatures much above the transition (above T_B^L). Insets: A comparison of our data far away from the transition and the backgrounds which would make them compatible with the $\Delta\sigma_{ab}(\varepsilon)$ corresponding to no cutoff (dotted lines), momentum cutoff (dashed lines) and total-energy cutoff (solid lines). See main text for details.

The in-plane resistivity versus temperature curves $\rho_{ab}(T)$ corresponding to these superconductors are presented in Figs. 1(a)–1(c). As usual,[2,3] the in-plane paraconductivity $\Delta\sigma_{ab}(\varepsilon)$ is obtained from these curves by just using $\Delta\sigma_{ab}(\varepsilon)\equiv\rho_{ab}^{-1}(\varepsilon)-\rho_{abB}^{-1}(\varepsilon)$, where $\rho_{abB}(\varepsilon)$ is the so-called background resistivity, which may be estimated by extrapolating through the transition the $\rho_{ab}(T)$ data measured well above the region where $\Delta\sigma_{ab}(\varepsilon)$ is to be analyzed. For doing such an extrapolation, we use a procedure particularly well adapted to obtain $\Delta\sigma_{ab}(\varepsilon)$ in the high-ε ($\varepsilon>0.1$) region (and, in fact, similar to the one already applied in Ref. 5 to the case of Y-123). This consists in locating the background fitting region far away from T_C (above at least $2T_C$) while, at the same time, requiring to the extrapolated background to quantitatively reproduce in the moderate ε range $10^{-2}\lesssim\varepsilon\lesssim10^{-1}$ both the amplitude and ε dependence of the $\Delta\sigma_{ab}(\varepsilon)$ results of the GGL approach for multilayered superconductors with no cutoff (see below and also Refs. 3 and 17). The same constraint determines T_C, which is found to be 19.6 K for LaSCO/0.1, 86.0 K for Bi-2212, and 115.7 K for Tl-2223 (see also Ref. 18). In these analyses we have always employed for $\rho_{abB}(T)$ the simplest T dependence compatible with the data (a second degree polynomial in the case of LaSCO/0.1, a straight line for Bi-2212, and a straight line plus a $\propto T^{-1}$ term for Tl-2223). The so-obtained backgrounds are represented as continuous lines in Figs. 1(a)–1(c) (main figures).

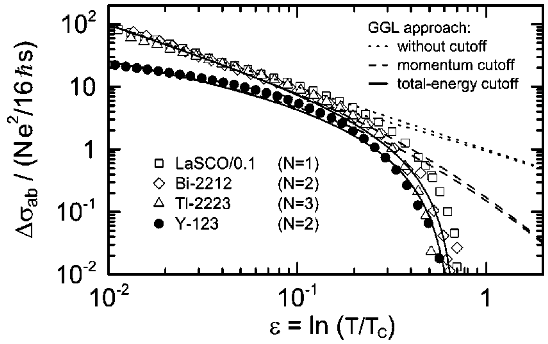

FIG. 2. In-plane paraconductivity of the different HTSC studied in this work, and their comparison with the GGL predictions with no cutoff (dotted lines), with a momentum cutoff (dashed lines), and with a total-energy cutoff (solid lines). The *y*-axis is normalized to account for the different number N of CuO_2 planes in the layer periodicity length, s, of each compound. Note that only the total-energy cutoff is able to reproduce the sharp fall-off observed in all these experimental curves. See main text for details.

The $\Delta\sigma_{ab}(\varepsilon)$ curves obtained for each of the highly anisotropic HTSC's studied here and also for the less anisotropic Y-123 (taken from Ref. 5) are shown in Fig. 2, together with their comparison with the GGL predictions under different cutoff conditions (see also below). To take into account the presence in each compound of a different number N of superconducting layers per layer periodicity length s these $\Delta\sigma_{ab}(\varepsilon)$ curves have been normalized by $Ne^2/16\hbar s$.[3,17] Both N and s are given by the crystallography of each superconductor (i.e., $N=1$ and $s=6.6$ Å for LaSCO/0.1, $N=2$ and $s=15.4$ Å for Bi-2212, $N=2$ and $s=11.7$ Å for Y-123, and $N=3$ and $s=17.8$ Å for Tl-2223). *They, therefore, cannot be considered as free parameters*. A first result easily visible in Fig. 2 is that such a normalization makes all the $\Delta\sigma_{ab}(\varepsilon)$ curves of the highly anisotropic HTSC's to collapse together, and this both in the low-ε ($\varepsilon\lesssim0.1$) and high-ε ($\varepsilon\gtrsim0.1$) regions. Note also that the shape of such a common $\Delta\sigma_{ab}(\varepsilon)$ curve is quite different in the low- and high-ε regions: For $\varepsilon\lesssim0.1$, $\Delta\sigma_{ab}(\varepsilon)$ follows a critical exponent -1, while for $\varepsilon\gtrsim0.1$ it undergoes a rapid fall, not describable by any simple power law in ε, towards reaching null $\Delta\sigma_{ab}(\varepsilon)$ at a reduced-temperature $0.4\lesssim\varepsilon^C\lesssim0.9$ ($0.4\lesssim\varepsilon^C\lesssim1.1$ in the case of LaSCO/0.1). The main source of such an error band is the uncertainty in the background subtraction, affecting mainly the exact location where $\Delta\sigma_{ab}(\varepsilon)$ becomes negligible but not the general shape of its fall-off. To estimate this error band we have followed the procedure described in Ref. 5 for the Y-123 samples. In particular, we have checked that T^C is independent of T_B^L, the lower limit of the background fitting region, provided that $T_B^L\gtrsim3.2T_C$ for LaSCO/0.1, $T_B^L\gtrsim2.5T_C$ for Bi-2212, and $T_B^L\gtrsim2.2T_C$ for Tl-2223.

Figure 2 also shows that the normalized $\Delta\sigma_{ab}(\varepsilon)$ curve of the less anisotropic compound Y-123 is different in the low-ε region to the one of the highly anisotropic HTSC's, both in amplitude and ε dependence. As already shown in detail in Refs. 3 and 17, the reason for these low-ε differences is that in Y-123 the correlation between adjacent superconducting layers produces both a lower effective number of planes fluctuating independently [affecting the amplitude of $\Delta\sigma_{ab}(\varepsilon)$] and a more 3D-like behavior (with critical exponent close to $-1/2$). Now then, in the high-ε region the $\Delta\sigma_{ab}(\varepsilon)$ curve of Y-123 collapses in the same curve as the highly anisotropic HTSC's. This is consistent with the fact that in Y-123 the out-of-plane superconducting coherence length $\xi_c(\varepsilon)$ becomes at $\varepsilon \gtrsim 0.1$ smaller than the distance between the closest CuO_2 planes (see also below) and, therefore, the system becomes 2D-like with an effective number of independently fluctuating planes equal to the number of CuO_2 layers.[3,17]

Figure 2 also shows the fits to the above data using the GGL expressions for $\Delta\sigma_{ab}(\varepsilon)$ in multilayered superconductors under different cutoff conditions. By considering the case that the interlayer couplings between different superconducting layers are of the same order of magnitude [as adequate for the HTSC's (Refs. 3,17)], such expressions were found in Ref. 5 to be

$$\Delta\sigma_{ab}(\varepsilon)=\frac{Ne^2}{16\hbar s}\left[\frac{1}{\varepsilon}\left(1+\frac{N^2B_{\mathrm{LD}}}{\varepsilon}\right)^{-1/2}+f(\varepsilon)\right], \qquad (1)$$

where $B_{\mathrm{LD}}\equiv(2\xi_c(0)/s)^2$ is the Lawrence-Doniach parameter, $\xi_c(0)$ is the out-of-plane GL coherence length amplitude, c is a cutoff constant of the order of unity, and $f(\varepsilon)$ is for the GGL approach with no cutoff $f(\varepsilon)\equiv 0$, for the conventional momentum cutoff $f(\varepsilon)\equiv-\delta-\delta^3c(\varepsilon+c+N^2B_{\mathrm{LD}}/2)$ with $\delta\equiv[(\varepsilon+c)(\varepsilon+c+N^2B_{\mathrm{LD}})]^{-1/2}$, and for the total-energy cutoff $f(\varepsilon)\equiv c^{-2}(\varepsilon-2c+N^2B_{\mathrm{LD}}/2)$. Such a total-energy cutoff condition may be written for 2D systems as

$$k_{xy}^2+\xi_{ab}^{-2}(\varepsilon)\leqslant c\,\xi_{ab}^{-2}(0), \qquad (2)$$

where k_{xy} is the in-plane momentum of the fluctuating modes, $\xi_{ab}(0)$ is the in-plane GL coherence length amplitude, and $\xi_{ab}(\varepsilon)=\xi_{ab}(0)\varepsilon^{-1/2}$. Equation (2) recovers the momentum cutoff condition when neglecting the localization-energy term $\xi_{ab}^{-2}(\varepsilon)$ (i. e., when $\varepsilon\ll c$). Note that in the total-energy cutoff all the fluctuations are suppressed for reduced temperatures above c, i.e., for temperatures above $T^C\equiv T_C\exp(c)$. In other words, c may be seen as the reduced-temperature $c=\varepsilon^C\equiv\ln(T^C/T_C)$ above which all fluctuations vanish. As reasoned in Ref. 11, the existence of such a reduced-temperature limit for the superconducting fluctuations is consistent with the fact that, due to the uncertainty principle, the superconducting coherence length at any temperature above or below T_C cannot be smaller than the Pippard coherence length ξ_0. This last condition directly leads to $\xi(\varepsilon^C)=\xi_0$. The value of ε^C (i.e., of c) will depend on each particular approach through the ε dependence of $\xi(\varepsilon)$. For instance, by using the mean-field reduced-temperature dependence of the coherence length,[10] $\xi(\varepsilon)=\xi(0)\varepsilon^{-1/2}$, then $\varepsilon\simeq[\xi(0)/\xi_0]^2$. On the grounds of the BCS approach in the clean limit $\xi(0)=0.74\,\xi_0$, and so $c=\varepsilon^C\simeq 0.55$ in these superconductors.

In comparing Eq. (1) with the data of the highly anisotropic HTSC, B_{LD} was always taken as zero and, therefore, only c is a free parameter, for which we get $0.4\lesssim c\lesssim 0.9$ ($0.4\lesssim c\lesssim 1.1$ for LaSCO/0.1). When comparing with the data of Y-123, also B_{LD} is a free parameter [or, equivalently, $\xi_c(0)$]. For this compound we have obtained[5] $\xi_c(0)=1.1\pm0.1$ Å and $0.5\lesssim c\lesssim 1$. Another central aspect shown in Fig. 2 is that in contrast with the momentum cutoff (dashed lines, with $c=0.7$), the inclusion of a total-energy cutoff in the GGL approach extends its applicability from the conventional $\varepsilon\ll 1$ condition up to ε^C.[10] In addition, the results of Fig. 2 seem to discard other regularization procedures, as, for instance, the one proposed by Patton and co-workers for the fluctuation induced diamagnetism in LTSC:[19] Such a penalization of the fluctuation probabilities (instead of a cutoff) do not lead to a sharp vanish of $\Delta\sigma_{ab}(\varepsilon)$ at any ε.

To further test if our resistivity data can discriminate between the different cutoff conditions, the insets of Figs. 1(a)–1(c) compare our measurements far away from the transition and the backgrounds that would make them compatible with the $\Delta\sigma_{ab}(\varepsilon)$ corresponding to such cutoffs. A similar test was used in the low-ε region by Carrington and co-workers.[20] As it can be easily seen in these insets, only the background compatible with a total-energy cutoff agrees with the high-temperature data within the experimental resolution (which is coincident with the data dispersion in those figures). When computing such backgrounds, we used the same values for the cutoff amplitudes and T_C as in our analyses above. However, using other values for these parameters do not change the conclusions of the comparison.

Finally, another interesting aspect of our data directly arises from the fact that no appreciable differences appear in the normalized $\Delta\sigma_{ab}(\varepsilon)$ curves of the underdoped LaSCO/0.1 with respect to the two other highly anisotropic (but optimally doped) HTSC. Therefore, the normal-state pseudogap characteristic of the underdoped HTSC (Ref. 4) does not seem to appreciably affect the superconducting fluctuations in LaSCO/0.1. Actually, our previous measurements[21] on the fluctuation magnetization in the same compound also support such a conclusion. This result contrasts with the proposals explaining the pseudogap in terms of preformed Cooper pairs, rather than as a normal-state phenomenon.[4] In particular, our present results suggest that also in the underdoped LaSCO/0.1 the formation by thermal fluctuations of coherent Cooper pairs is limited to reduced-temperatures below $0.4\lesssim\varepsilon^C\lesssim 1.1$. This value of ε^C is in striking good agreement with the value $\varepsilon^C\simeq 0.6$ that we may obtain on the grounds of the BCS approach (see before and Ref. 11). Moreover, below T^C the collective behavior of these Cooper pairs may be described in terms of the mean-field GGL approach regularized under a total-energy cutoff. This last finding also seems to disagree with the proposals linking the pseudogap phenomena to dominant phase fluctuations.[4]

In conclusion, the experimental data presented here for the in-plane paraconductivity in different HTSC's suggest that its high-ε behavior is universal: Although such a behavior cannot be described in terms of a critical exponent in ε, in all the cases we observe the same type of rapid fall-off at the same (well within the experimental uncertainties) reduced temperature $\varepsilon^C \simeq 0.7$.[23] This value is in striking good agreement with the one that can be obtained by combining the GGL and BCS approaches and by taking into account that the uncertainty principle imposes a limit to the shrinkage of the superconducting wave function when the reduced-temperature increases. Our experimental results strongly suggest that the inclusion of such a constraint extends the validity of the *multilayered*[22] GGL approximation up to ε^C. Other implications of our findings beyond the superconducting fluctuations issue, including those in the descriptions of the pseudogap in underdoped HTSC, will deserve further studies.

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[10] The conventional GGL approach, including the $\varepsilon^{-1/2}$ dependence of $\xi(\varepsilon)$, is expected to be formally valid only in the ε-region $\varepsilon_{\mathrm{LG}} \lesssim \varepsilon \ll 1$, where $\varepsilon_{\mathrm{LG}}$ is the so-called Levanyuk-Ginzburg reduced temperature (Ref. 3). At high reduced temperatures, when $\xi(\varepsilon)$ becomes of the order of $\xi(0)$, various new terms not included in the conventional GGL functional (e.g., the powers higher than two of the gradient of the order parameter) could become particularly relevant, or even it could be not applicable any mean-field-like approach. However, our present results strongly suggest that the limitation of the shrinkage of the superconducting wave function is the dominant effect when ε approaches ε^C, and that both the GGL approach under a total-energy cutoff and the mean-field critical exponent of $\xi(\varepsilon)$, $x = -1/2$, remains qualitatively valid even up to ε^C.

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