

Comment on “High-field studies of superconducting fluctuations in high- T_c cuprates: Evidence for a small gap distinct from the large pseudogap”

M. V. Ramallo, C. Carballeira, R. I. Rey, J. Mosqueira, and F. Vidal

LBTS, Departamento de Física da Materia Condensada, Universidade de Santiago de Compostela, ES-15782, Spain

(Received 19 September 2011; published 29 March 2012)

By using high magnetic field data to estimate the background conductivity, Rullier-Albenque and coworkers have recently published [Phys. Rev. B **84**, 014522 (2011)] experimental evidence that the in-plane paraconductivity in cuprates is almost independent of doping. In this Comment we also show that, in contrast with their claims, these useful data may be explained at a quantitative level in terms of the Gaussian-Ginzburg-Landau approach for layered superconductors, extended by Carballeira and coworkers to high reduced temperatures by introducing a total-energy cutoff [Phys. Rev. B **63**, 144515 (2001)]. When combined, these two conclusions further suggest that the paraconductivity in cuprates is conventional, i.e., associated with fluctuating superconducting pairs above the mean-field critical temperature.

DOI: [10.1103/PhysRevB.85.106501](https://doi.org/10.1103/PhysRevB.85.106501)

PACS number(s): 74.40.-n, 74.72.-h, 74.25.F-, 74.62.En

In a recent work,¹ Rullier-Albenque and coworkers presented detailed measurements of the in-plane paraconductivity $\Delta\sigma_{SF}(T,0)$ and of the fluctuation-induced magnetoconductivity $\Delta\sigma_{SF}(T,H)$ above the superconducting transition temperature T_c of $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ superconductors, as a function of the oxygen content and with magnetic fields up to 60 T. As they estimate the background contributions to the resistivity by means of the high reduced-magnetic field data, instead of the usual temperature extrapolations,² their results provide a useful confirmation of earlier findings obtained by Currás and coworkers³ and then by other authors:^{4,5} Even in the high reduced-temperature region, for $\varepsilon \equiv \ln(T/T_c) \gtrsim 0.1$ (where the influence of the opening of a pseudogap in the normal state of the underdoped cuprates could be more important), $\Delta\sigma_{SF}(T,0)$ is almost independent of the doping level. As already stressed in Refs. 3 and 6, this conclusion, that applies to all samples not severely affected by inhomogeneities, was inferred in these different works directly from the $\Delta\sigma_{SF}(T,0)$ data and, therefore, is “model independent.” These results strongly suggest that the in-plane paraconductivity in cuprates is, including its onset,⁷ independent of the opening of a pseudogap in the normal state.

The next step to establish the nature itself of the corresponding superconducting fluctuations is to check if the measured $\Delta\sigma_{SF}(T,0)$ could be described in terms of the different versions of the phenomenological Gaussian-Ginzburg-Landau (GGL) approach for layered superconductors. This task was also attempted in Ref. 1, but, unfortunately, without taking into account the multilayering effects^{8,9} and also, when analyzing their data on the grounds of the so-called *extended GGL approach* that includes a *total-energy cutoff*,^{10,11} by using an expression for $\Delta\sigma_{SF}(T,0)$ inadequate for the studied compounds. By overcoming these shortcomings we will show here that, contrary to the conclusions in Ref. 1, the in-plane paraconductivity data are in excellent quantitative agreement, also in the high- ε region, with the extended GGL approach, providing then an interesting confirmation of previous analyses obtained in other cuprates with different dopings.^{3,4,10-12} Note also that the onset of the in-plane paraconductivity in cuprate superconductors with different dopings is still at present a central and debated aspect that is receiving considerable

attention (see, e.g., Ref. 13). So, probably one of the most useful implications of the experimental data presented in Ref. 1 is to provide, when correctly analyzed, a further confirmation of the adequacy of the GGL approach with a total-energy cutoff to describe the onset of the superconducting fluctuations and the in-plane paraconductivity behavior at high reduced temperatures.

Let us note that the total-energy cutoff, introduced in the GGL calculations of the paraconductivity by Carballeira and coworkers,¹⁰ directly results from the limits imposed by the uncertainty principle to the shrinkage of the superconducting wave function above the superconducting transition, as proposed by Vidal and coworkers.¹¹ This cutoff has then a fundamental origin, and it solves the well-known inconsistencies at large ε of the GGL approach without a cutoff or with the popular momentum cutoff,¹⁴ while recovering for low ε the conventional (without a cutoff) GGL results, as explained in detail in Refs. 3, 10, and 11. So, one may note already here without the need of any detailed comparison that, contrary to the conclusion suggested in Sec. VIII A of Ref. 1, the introduction of the *intrinsiclike* total-energy cutoff “privileges” the high- ε region (“the cutoff behavior”) but without appreciably affecting the low- ε region: In the case of the paraconductivity, the influence of such a cutoff is almost inappreciable in the low reduced-temperature region, for $\varepsilon \lesssim 0.03$, it becomes relatively moderate (could be absorbed by slightly changing the parameters involved) for $0.03 \lesssim \varepsilon \lesssim 0.1$, and it only becomes important in the high reduced-temperature region, for $\varepsilon \gtrsim 0.1$.

A comparison between the data of Fig. 24 and Eq. (24) in Ref. 1 would already provide a crude confirmation of the qualitative considerations indicated above, even when using as the effective interlayer periodicity length, s , the crystallographic unit cell length, $c = 11.7 \text{ \AA}$ for $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$. However, Eq. (24) agrees only in the 2D limit with the expression actually calculated by Carballeira and coworkers for the so-called *direct* (Aslamazov-Larkin) contribution to $\Delta\sigma_{SF}(T,0)$ under a total-energy cutoff.¹⁰ This limit is defined by $2\xi_c(0)\varepsilon^{-1/2} \ll s$, where $\xi_c(0)$ is the transversal coherence length amplitude. In $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ such a limit will not apply when $\varepsilon \lesssim 0.1$. So, to perform a quantitative comparison, we

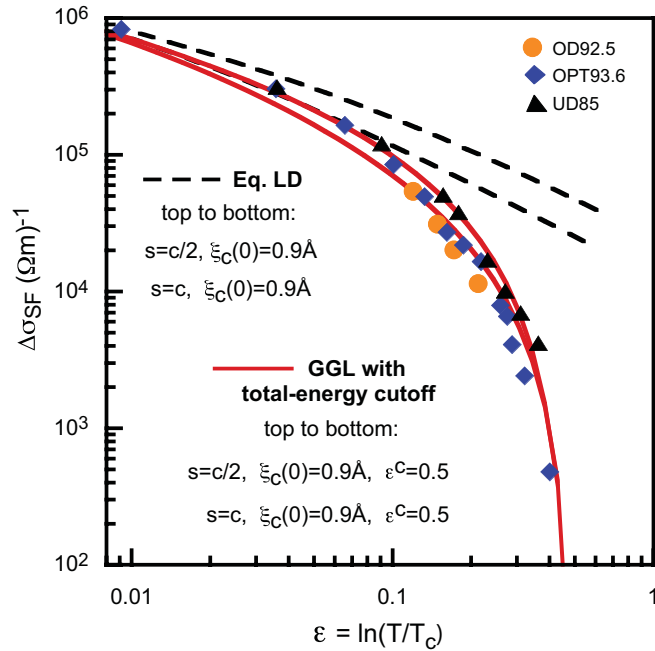


FIG. 1. (Color online) Comparison between some of the experimental data for the in-plane paraconductivity in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ superconductors with different dopings, summarized in Fig. 24 of Ref. 1, with the expression for the GGL paraconductivity under a total-energy cutoff, calculated by Carballeira and coworkers for multilayered superconductors [Eq. (9) of Ref. 10]. In doing this comparison we have used the c -direction coherence length proposed in Ref. 1, an effective interlayer distance $s = c/2 = 5.85 \text{ \AA}$, and a total-energy cutoff parameter $\varepsilon^c = 0.5$, which is close to the value that one may estimate in a BCS-like scenario (Ref. 11). We also show (upper dashed line) the GGL prediction without cutoff [Eq. (10) of Ref. 1], evaluated by using again $s = c/2$, and that following the notation used in Ref. 1 is labeled Eq. LD in this figure. The lower continuous and dashed curves are the in-plane paraconductivity neglecting multilayering effects, i.e., calculated by using $s = c$ and the same values as before for the remaining parameters.

must use the general expression for $\Delta\sigma_{SF}(T,0)$ given by Eq. (9) of Ref. 10, and also one must take into consideration that these compounds have two superconducting layers per unit cell length and that the corresponding multilayering effects may affect both the amplitude and the ε dependence of the in-plane paraconductivity.^{8,9} As it is now well established,^{9,15} in the case of $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ these multilayering effects may be crudely taken into account by just using an effective interlayer distance $s \simeq c/2 = 5.85 \text{ \AA}$. This last approximation, that was already used by Carballeira and coworkers when analyzing the paraconductivity measured in optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ single crystals and thin films,¹⁰ means that in these compounds the two superconducting layers in the periodicity length c may fluctuate as different degrees of freedom, a conclusion that was confirmed experimentally in other works.^{9,15} Note that multilayering does not imply any value for $\xi_c(0)$ [in particular, it does not impose at all $\xi_c(0) = 0$] and, obviously, it does not exclude the presence of a 2D-3D transition of the superconducting fluctuations when approaching T_c from above. This point was clearly stressed in Refs. 9, 10, and 15,

where by analyzing consistently three different observables it was also established experimentally the absence of indirect (Maki-Thompson) and DOS effects on the paraconductivity in cuprate superconductors.

The comparison between the experimental data of Fig. 24 in Ref. 1 and Eq. (9) in Ref. 10 is presented in Fig. 1 of this Comment. We have used $s = c/2$, and for the total-energy cutoff parameter^{10,11} $\varepsilon^c = 0.5$, which is close to the value estimated in a BCS-like scenario.¹¹ For the remaining parameter, $\xi_c(0)$, we have used the same value as proposed in Ref. 1, $\xi_c(0) = 0.9 \text{ \AA}$ (which is close to the value used in Refs. 9–11 for optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$). The resulting $\Delta\sigma_{SF}(T,0)$ is the upper solid curve in Fig. 1. As one may appreciate in that figure, the in-plane paraconductivity data for the different $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ superconductors presented in Fig. 24 of Ref. 1 agree at a quantitative level, in the whole range of ε values and doping levels covered by these data, with the GGL prediction for the direct (Aslamazov-Larkin) fluctuation contribution in bilayered superconductors under a total-energy cutoff proposed by Carballeira and coworkers in Ref. 10. For completeness, we also present in that figure (lower solid curve) the corresponding prediction in the absence of multilayering, i.e., the one obtained by using in Eq. (9) of Ref. 10 $s = c = 11.7 \text{ \AA}$ and the same values as before for the remaining parameters, i.e., $\varepsilon^c = 0.5$ and $\xi_c(0) = 0.9 \text{ \AA}$. Although for $\varepsilon < 0.1$ the agreement is somewhat worse than when the multilayering effects are taken into account, even in this case the improvement obtained by the introduction of the total-energy cutoff is evident, mainly when compared with the GGL predictions without cutoff (dashed curves in Fig. 1, labeled as Eq. LD following the notation in Ref. 1). The latter were evaluated by using Eq. (10) of Ref. 1 with either $s = c/2$ or $s = c$.

In conclusion, by analyzing, just as an example, the results of Fig. 24 of Ref. 1, we have shown that contrary to the claims of Rullier-Albenque and coworkers, their paraconductivity results may be explained at a quantitative level in terms of the *extended* GGL approach. This result further confirms, at least for dopings above 0.1 hole/ CuO_2 ,¹⁶ the conventional nature of the superconducting fluctuations in cuprates (GGL-like, associated with fluctuating superconducting pairs above the mean-field critical temperature), independently of their doping and of the temperature region above T_c , as also earlier concluded by Currás and coworkers³ by analyzing the in-plane excess conductivity in other cuprates (see also Refs. 4–6 and 10–12). They also seem to confirm that the total-energy cutoff parameter is, well within the experimental uncertainties, doping independent and close to the value that may be estimated in a BCS-like scenario.¹¹ The example studied here also suggests the way to analyze in terms of the extended GGL approach the remaining measurements of Ref. 1. It would also be interesting to compare the data acquired under high reduced-magnetic fields with results for the fluctuation-induced diamagnetism in $\text{La}_{2-x}\text{Sr}_x\text{Cu}_2\text{O}_4$ superconductors with different dopings, which follow the GGL predictions even for finite reduced-magnetic fields.¹⁷

This work has been supported by the MICINN project FIS2010-19807 and by the Xunta de Galicia projects 2010/XA043 and 10TMT206012PR. All these projects are cofunded by ERDF from the European Union.

- ¹F. Rullier-Albenque, H. Alloul, and G. Rikken, *Phys. Rev. B* **84**, 014522 (2011).
- ²The need of an always somewhat arbitrary background term to determine the paraconductivity is a consequence of the fact that the theoretical approaches calculate the fluctuation contribution separately from the noncritical contributions. These ambiguities affect, therefore, any background estimation, including those obtained by quenching the superconductivity by high reduced-magnetic fields. So, the comparison between the paraconductivities obtained by using different background procedures provides then an important test of consistency.
- ³S. R. Currás, G. Ferro, M. T. González, M. V. Ramallo, M. Ruibal, J. A. Veira, P. Wagner, and F. Vidal, *Phys. Rev. B* **68**, 094501 (2003); see also J. Viña, J. A. Campá, C. Carballeira, S. R. Currás, A. Maignan, M. V. Ramallo, I. Rasines, J. A. Veira, P. Wagner, and F. Vidal, *ibid.* **65**, 212509 (2002).
- ⁴See, e.g., S. H. Naqib, J. R. Cooper, J. L. Tallon, R. S. Islam, and R. A. Chakalov, *Phys. Rev. B* **71**, 054502 (2005); S. Caprara, M. Grilli, B. Leridon, and J. Lesueur, *ibid.* **72**, 104509 (2005); C. A. C. Passos, M. T. D. Orlando, J. L. Passamai Jr., E. V. L. de Mello, H. P. S. Correa, and L. G. Martinez, *ibid.* **74**, 094514 (2006).
- ⁵B. Leridon, J. Vanacken, T. Wambecq, and V. V. Moshchalkov, *Phys. Rev. B* **76**, 012503 (2007); In this work, the background conductivity in an underdoped cuprate was estimated by using high magnetic fields to suppress the superconductivity. The relatively high reduced temperature at which the paraconductivity onset is observed, $\varepsilon \simeq 0.9$, may be a consequence of the unavoidable background uncertainties associated with the normal-state magnetoresistivity above T_c [see, e.g., J. Vanacken, L. Weckhuysen, T. Wambecq, P. Wagner, and V. V. Moshchalkov, *Physica C* **432**, 81 (2005)].
- ⁶F. Vidal, M. V. Ramallo, G. Ferro, and J. A. Veira, in *New Challenges in Superconductivity: Experimental Advances and Emerging Theories*, edited by J. Ashkenazi, M. V. Eremin, J. L. Cohn, I. Eremin, D. Manske, D. Pavuna, and F. Zuo (Springer, New York, 2005), p. 85 (also available as e-print [arXiv:cond-mat/0603074](https://arxiv.org/abs/cond-mat/0603074)).
- ⁷The paraconductivity behavior at high reduced temperatures, including the temperature location of its onset, is particularly sensitive to the background estimations, and the use of linear temperature extrapolations may introduce considerable errors. This point was clearly stressed in Ref. 3, where it was detailed a procedure to avoid these shortcomings when the normal-state resistivity is nonlinear. Although these difficulties have been described in detail in different works (see, e.g., Refs. 3–6 and references therein), some of them were revisited in Ref. 1 (in Sec. VI). In any case, the central aspect here is the fact that these different background procedures, including the one of Ref. 1, lead to a similar doping-independent behavior of the in-plane paraconductivity at high reduced temperatures, as first observed in Ref. 3. In view of this conclusion, any debate about the best procedure to estimate the background becomes superfluous here.
- ⁸K. Maki and R. S. Thompson, *Phys. Rev. B* **39**, 2767 (1989); R. A. Klemm, *ibid.* **41**, 2073 (1990).
- ⁹For a review of the multilayering effects on the superconducting fluctuations, see F. Vidal and M. V. Ramallo, in *The Gap Symmetry and Fluctuations in High- T_c Superconductors*, edited by J. Bok, G. Deutscher, D. Pavuna, and S. A. Wolf (Plenum, London, 1998), p. 443. See also M. V. Ramallo and F. Vidal, *Phys. Rev. B* **59**, 4475 (1999).
- ¹⁰C. Carballeira, S. R. Currás, J. Viña, J. A. Veira, M. V. Ramallo, and F. Vidal, *Phys. Rev. B* **63**, 144515 (2001).
- ¹¹F. Vidal, C. Carballeira, S. R. Currás, J. Mosqueira, M. V. Ramallo, J. A. Veira, and J. Viña, *Europhys. Lett.* **59**, 754 (2002).
- ¹²See, e.g., D.-N. Peligrad, M. Mehring, and A. Dulčić, *Phys. Rev. B* **69**, 144516 (2004); Y. Liu, S. L. Wan, and X. G. Li, e-print [arXiv:cond-mat/0602225](https://arxiv.org/abs/cond-mat/0602225); T. Aoki, Y. Oikawa, C. Kim, T. Tamura, H. Ozaki, and N. Mori, *Physica C* **463-465**, 126 (2007); N. Mori, *ibid.* **469**, 970 (2009); and references therein. For other applications of the total-energy cutoff see, e.g., I. Puica and W. Lang, *Phys. Rev. B* **68**, 054517 (2003); **68**, 212503 (2003).
- ¹³See, e.g., L. S. Bilbro, R. Valdés Aguilar, G. Logvenov, O. Pelleg, I. Božović, and N. P. Armitage, *Nat. Phys.* **7**, 298 (2011); A. Dubroka, M. Rössle, K. W. Kim, V. K. Malik, D. Munzar, D. N. Basov, A. A. Schafgans, S. J. Moon, C. T. Lin, D. Haug, V. Hinkov, B. Keimer, Th. Wolf, J. G. Storey, J. L. Tallon, and C. Bernhard, *Phys. Rev. Lett.* **106**, 047006 (2011); P. M. C. Rourke, I. Mouzopoulou, X. Xu, C. Panagopoulos, Y. Wang, B. Vignolle, C. Proust, E. V. Kurganova, U. Zeitler, Y. Tanabe, T. Adachi, Y. Koike, and N. E. Hussey, *Nat. Phys.* **7**, 455 (2011). See also our comment on this last work in J. Mosqueira *et al.*, e-print [arXiv:1112.6104](https://arxiv.org/abs/1112.6104).
- ¹⁴Although limited to optimally-doped $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ samples, the sharp decrease of the paraconductivity at high reduced temperatures was earlier analyzed in terms of the GGL approach with the conventional momentum cutoff by various groups. See, e.g., P. P. Freitas, C. C. Tsuei, and T. S. Plaskett, *Phys. Rev. B* **36**, 833 (1987); R. Hopfengärtner, B. Hensel, and G. Saemann-Ischenko, *ibid.* **44**, 741 (1991); A. Gauzzi and D. Pavuna, *ibid.* **51**, 15420 (1995). These results show already the failure of such a momentum cutoff for reduced temperatures above 0.1.
- ¹⁵M. V. Ramallo, A. Pomar, and F. Vidal, *Phys. Rev. B* **54**, 4341 (1996).
- ¹⁶The most underdoped samples studied in Ref. 1 may be severely affected by T_c inhomogeneities associated with chemical disorder (intrinsic or extrinsic) [see, e.g., J. Mosqueira, L. Cabo and F. Vidal, *Phys. Rev. B* **80**, 214527 (2009)]; The influence of T_c inhomogeneities on the electrical resistivity rounding above the average T_c was earlier addressed by J. Maza and F. Vidal, *Phys. Rev. B* **43**, 10560 (1991). For a review of the effects of the T_c inhomogeneities with long characteristic lengths (larger than the in-plane coherence length amplitude) on the measurements around the average T_c in cuprate superconductors, see F. Vidal, J. A. Veira, J. Maza, J. Mosqueira, and C. Carballeira, in *Material Science, Fundamental Properties and Future Electronic Applications of High- T_c Superconductors*, edited by S. L. Dreschler and T. Mishonov (Kluwer, Dordrech, 1999), p. 289; also available as e-print [arXiv:cond-mat/0510467](https://arxiv.org/abs/cond-mat/0510467).
- ¹⁷C. Carballeira, J. Mosqueira, A. Revcolevschi, and F. Vidal, *Phys. Rev. Lett.* **84**, 3157 (2000); *Physica C* **384**, 185 (2003); J. Mosqueira, L. Cabo, and F. Vidal, *Phys. Rev. B* **80**, 214527 (2009); The decay of the superconducting fluctuations in the presence of high reduced-magnetic fields, observed through magnetization measurements in low- T_c superconductors, was also interpreted on the grounds of the extended GGL approach in F. Soto, C. Carballeira, J. Mosqueira, M. V. Ramallo, M. Ruibal, J. A. Veira, and F. Vidal, *Phys. Rev. B* **70**, 060501 (2004).