Comment on "Temperature range of superconducting fluctuations above T_c in $YBa_2Cu_3O_{7-\delta}$ single crystals"

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Contrary to the starting assumption of Grbić *et al.* [Phys. Rev. B **83**, 144508 (2011)], here we will argue that a 16-T magnetic field is not enough to quench all superconducting fluctuations above T_c in $YBa_2Cu_3O_{7-\delta}$. We conclude that through their measurements of microwave absorption these authors actually determine the AC fluctuation magnetoconductivity at 16 T, instead of the zero-field AC paraconductivity as they contend. So the temperature proposed by Grbić *et al.* for the onset of the superconducting fluctuations, T', will correspond to the one at which the finite-field effects at 16 T become measurable in their experiments and the actual fluctuation onset will be located well above T'. These conclusions, which also concern influential recent publications on that issue, are confirmed by analyzing some of the Grbić *et al.* data on the grounds of the Gaussian Ginzburg-Landau approach for the finite-field (or Prange) fluctuation regime.

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The starting assumption of the Grbić *et al.* analysis of their interesting microwave absorption measurements in $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals is "that the field of 16 T is well sufficient to suppress all superconducting fluctuations above the zero field T_c" [1]. Accordingly, these authors claimed to extract the real part of the in-plane AC paraconductivity in zero magnetic field, as "the difference of the curves [of the conductivities] measured in zero field and in the field of 16 T." The temperature at which this difference becomes measurable with their experimental resolution, denoted by T', was then identified with the onset of the superconducting fluctuations. To further support their conclusions, Grbić *et al.* claimed that the so-obtained zero-field AC paraconductivity may be quantitatively explained on the grounds of the Gaussian Ginzburg-Landau (GGL) scenario.

In this Comment, we first stress that a magnetic field amplitude of 16 T is much smaller than different proposals for the upper critical magnetic field amplitude $H_{c2}(0)$ of YBCO. As it is well known since the pioneering studies of Tinkham and co-workers in low-temperature superconductors (LTSCs) [2,3], a field amplitude much smaller than $H_{c2}(0)$ is not enough to suppress the superconducting fluctuations above T_c. As we will stress here, such a conclusion is general and will apply also to the high-temperature superconductors (HTSCs). As a consequence, instead of the real part of the zero-field in-plane AC paraconductivity, we will argue that the measurements of Grbić *et al.* determine the real part of the total in-plane AC magnetoconductivity at 16 T and that the onset temperature of the superconducting fluctuations T_{onset} will be located well above T'. These conclusions are confirmed by analyzing, for example, some of the data of Ref. [1] for the overdoped sample on the grounds of the GGL approach for the finite-field (or Prange) fluctuation regime [3–5] and also by taking into account the frequency dependence of the AC conductivity [3,6]. Although Ref. [1] was published nine years ago, the interest and suitability of our present Comment is enhanced by the fact that some of the assumptions and/or conclusions of the paper that we now question are still being used in influential studies to support different phenomenological descriptions of the rounding effects around T_c [7–9], which are in some cases contradictory [10].

The central aspect of the procedure used by Grbić *et al.* was to approximate the zero-field in-plane paraconductivity $\Delta\sigma_{ab}(\varepsilon, 0) \equiv \sigma_{ab}(\varepsilon, 0) - \sigma_{abB}(\varepsilon, 0)$ by the in-plane magnetoconductivity $\Delta\tilde{\sigma}_{ab}(\varepsilon, H) \equiv \sigma_{ab}(\varepsilon, 0) - \sigma_{ab}(\varepsilon, H)$. In these expressions, $\sigma_{ab}(\varepsilon, H)$ and $\sigma_{abB}(\varepsilon, H)$ are the as-measured and background (or normal-state) in-plane electrical conductivities, respectively, at a reduced temperature $\varepsilon \equiv \ln(T/T_c)$ and at a magnetic field H, applied perpendicular to the *ab* planes. However, this simple and well-known approximation (see e.g., Refs. [3,5,11–15] and references therein), which would allow to estimate the zero-field paraconductivity from two directly measurable observables, is applicable only if two conditions are fulfilled: first, if the normal-state magnetoconductivity can be neglected, i.e., if $\sigma_{abB}(\varepsilon, 0) \approx \sigma_{abB}(\varepsilon, H)$, and second, if it is used a field amplitude H_q large enough to quench the superconducting fluctuations at all reduced temperatures, i.e., $\sigma_{ab}(\varepsilon, H_q) = \sigma_{abB}(\varepsilon, H_q)$.

The adequacy of the first approximation noted above, namely, the smallness of the normal-state magnetoconductivity when compared with the one associated with the superconducting fluctuations, was proved earlier in different HTSCs, including YBCO, at least at a qualitative level and up to moderate reduced temperatures and magnetic fields [3,5,11–15]. In what concerns the amplitude of H_q, the pioneering measurements of Tinkham and co-workers of the fluctuation-induced diamagnetism in several LTSCs suggested that it is of the order of $H_{c2}(0)$, a result that these authors related to the shrinkage of the superconducting coherence length at high reduced magnetic fields and temperatures, already suggesting the generality of their finding [2,3]. These conclusions were later confirmed by measurements in other LTSCs [16] and also in a HTSC with a low $H_{c2}(0)$ [17]. The corresponding experimental results were accounted for at a quantitative level on the grounds of the GGL scenario by introducing a so-called total-energy cutoff, which takes into account the limits imposed by the uncertainty principle to the shrinkage of the superconducting coherence length [18]. Measurements of the DC paraconductivity under high magnetic fields (up to 60 T) in different HTSCs, including YBCO compounds, also support $H_q \sim H_{c2}(0)$ [14,15].

The question now, therefore, is if the $H_{c2}(0)$ values of the samples studied in Ref. [1] are of the order of or less than 16 T, the largest magnetic field used in these measurements. As already stressed in Tinkham's textbook [3], $H_{c2}(0)$ in HTSCs is poorly defined, because of fluctuation rounding of the transition. In fact, even in the case of the highly studied YBCO compounds around their optimal doping, the discrepancies between different determinations of $H_{c2}(0)$ remain up to now very important, the proposals leading to field amplitudes between 100 and 400 T [3,5,8,9,11–13,15,19]. For the most underdoped YBCO compound studied in Ref. [1], with $T_c = 57$ K, different proposals lead to $\mu_0 H_{c2}(0)$ values between 30 and 90 T [13,15,19], in any case still much larger than the field amplitudes used in Ref. [1]. For both compounds, the largest $H_{c2}(0)$ values are those extracted from the analysis of the superconducting fluctuations around T_c on the grounds of the Ginzburg-Landau (GL) scenario, this last procedure probably being, as suggested by the above comment in Tinkham's textbook, the most adequate to determine $H_{c2}(0)$ in HTSC.

The qualitative analysis summarized above already suggests that T' in Ref. [1] actually corresponds to the temperature at which the finite-field effects at 16 T become measurable in their experiments. On the grounds of the GGL approach, these effects are expected to be appreciable when ε becomes of the order of the reduced magnetic field $h \equiv H/H_{c2}(0)$ [2–5,11], i.e.,

$$T' \approx T_c(1+h), \tag{1}$$

an approximate relationship which will break down when $H \approx H_{c2}(0)$. In Ref. [1] the measured parameters are T_c and T' (16 T), so the easiest way to check the applicability of Eq. (1) is to estimate the corresponding $H_{c2}(0)$ values. This leads to $\mu_0 H_{c2}(0) \sim 200$ T for sample OD89 (with $T_c = 89.4$ K and $T' - T_c \approx 7$ K) and $\mu_0 H_{c2}(0) \sim 40$ T for sample UD57 (with $T_c = 57.2$ K and $T' - T_c \approx 23$ K). These $H_{c2}(0)$ values are in reasonable agreement with the ones in the literature,[3,5,11–13,15,19] taking into account the error sources affecting both the experimental parameters and Eq. (1), in particular the assumption that the normal-state magnetoconductivity may be neglected. Note also that the seemingly much wider temperature range of the superconducting fluctuations observed in the most underdoped sample with $T_c \approx 57$ K (when compared to the widths observed in the almost optimally doped samples), a result claimed by Grbić *et al.* [1] as "the most intriguing in the current controversy about the nature of the pseudogap in deeply underdoped HTSC," may be easily explained by just taking into account in Eq. (1) the much lower value of the upper critical field in this deeply underdoped sample.

The finite-field effects predicted by the GGL approach may also easily explain the central result above T_c in Fig. 6 of Ref. [1]: the overlapping a few degrees (7–8 K) above T_c (denoted by T') of the two curves of the in-plane complex conductivity of sample UD87 measured under 0 and 16 T. This result just confirms the presence of the expected field effects below $T'(16\,\mathrm{T})$ and it does not exclude at all the presence of appreciable superconducting fluctuations in the entire temperature region above T' covered by these data. So the conclusion of Ref. [1] that, "by taking the difference of the conductivities in the zero field and in 16 T field, one may constrict a reliable procedure for extracting the pure superconducting fluctuation contribution to the conductivity above the zero field T_c" is unfounded.

A quantitative check of the crude conclusions summarized above may be done on the grounds of the GGL approach by analyzing, for example, the results on the real part (see Ref. [20]) of the AC measurements presented in Fig. 9(a) of Ref. [1] for the overdoped sample OD89, which is the closer to the prototypical optimally doped YBCO. As commented above, these data actually correspond to the AC in-plane magnetoconductivity $\Delta\tilde{\sigma}_{ab}(\varepsilon, 16\,\mathrm{T})$. By neglecting the normal-state magnetoconductivity when compared with the one associated with the superconducting fluctuations, these data may then be approximated as

$$\sigma_{ab}(\varepsilon,0) - \sigma_{ab}(\varepsilon,16\,\mathrm{T}) \approx S(\omega,T)[\Delta\sigma_{ab}(\varepsilon,0) - \Delta\sigma_{ab}(\varepsilon,16\,\mathrm{T})]. \tag{2}$$

For the prefactor $S(\omega, T)$, which takes into account the high-frequency influence on the AC conductivity, we have used Eq. (12) of Ref. [6], as in Ref. [1]. In turn, for the DC paraconductivity $\Delta\sigma_{ab}(\varepsilon, H)$, we have used Eq. (8) in Ref. [5].

The solid line in Fig. 1 corresponds to the best fit of Eq. (2) to the σ_{1ab} data in Fig. 9(a) of Ref. [1]. In doing this fitting we have excluded the data within the transition width ΔT_c reported in Ref. [1] ($\varepsilon < \Delta T_c/T_c$, dashed bar) probably affected by T_c inhomogeneities [21], and the only free parameter was the cutoff Λ arising in $S(\omega, T)$. For the remaining parameters, those arising in $\Delta\sigma_{ab}$ (the in-plane and transverse coherence lengths, the relative GL relaxation time, and the total-energy cutoff), we have used the values recently obtained in optimally doped YBCO through measurements of the precursor diamagnetism and the DC paraconductivity and magnetoconductivity, summarized in Table 2 of Ref. [5]: $\xi_{ab}(0) = 1.1$ nm, $\xi_c(0) = 0.11$ nm, $\tau_{\mathrm{rel}} = 1$, and $\varepsilon_c = 0.55$. Our procedure then ensures a crucial check of consistency with previous DC studies [22]. Another important aspect of our present analysis is that it leads to $\Lambda = 0.23$, in reasonable agreement with the theoretical expectations [6] (discussed below). Note also that, as the ε region where the field effects at 16 T become relevant is relatively close to T_c, the resulting fit will not be appreciably affected by a cutoff in the DC paraconductivity (although the total-energy cutoff is crucial to precisely locate T_{onset} in the GGL scenario [5,18]).

Taking into account the crude approximation used to estimate the high-frequency effects (although similar to the one used in Ref. [1]) and that the only free parameter was the

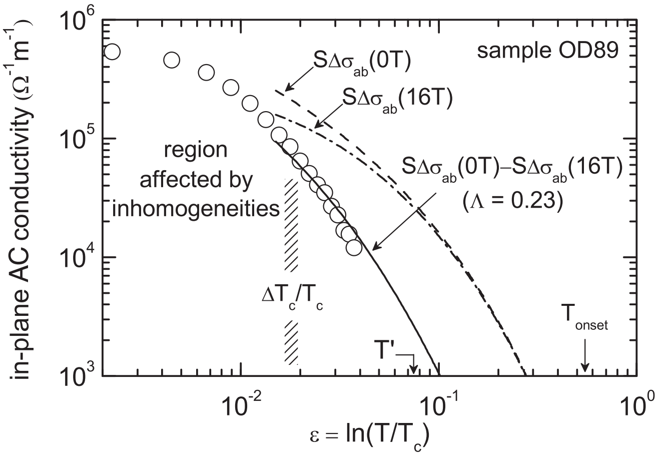

FIG. 1. The solid line corresponds to the best fit of the in-plane magnetoconductivity given by Eq. (2) to the σ_{1ab} data in Fig. 9(a) of Ref. [1] for the overdoped sample OD89. This solid line was approximated as the difference between the in-plane AC paraconductivity measured without a field and with 16 T (dashed lines). This fit excludes data within the transition width (below order of $\Delta T_c/T_c$), which may be deeply affected by T_c inhomogeneities. In this GGL scenario, the well-defined onset temperature of the superconducting fluctuations is denoted by T_{onset} (which corresponds to a total-energy cutoff of 0.55), whereas T' was proposed in Ref. [1]. However, as it may be appreciated, this corresponds instead, well within the experimental resolution, to the onset of the field effects at 16 T (i.e., when $\varepsilon \approx h$). For other details see the text.

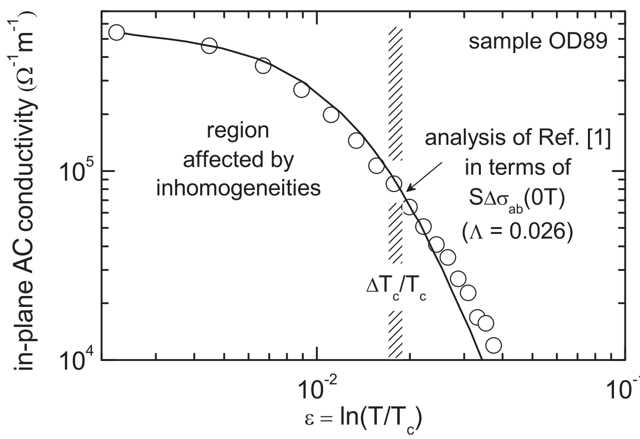

FIG. 2. Analysis performed in Ref. [1] [see Fig. 9(a) therein] of the same data that we have analyzed in our Fig. 1. However, in this case these data were compared with the zero-field in-plane AC paraconductivity, with all fitting parameters free and without excluding the data points closer to T_c. One may appreciate here that the agreement is good in the region probably affected by T_c inhomogeneities, but worse at higher ε (see the text and Ref. [21]).

cutoff Λ arising in $S(\omega, T)$, the results summarized in Fig. 1 may be considered reasonable and compare favorably with the analysis performed in Ref. [1]. This conclusion is illustrated in Fig. 2, where the same data were compared in Ref. [1] with the zero-field in-plane paraconductivity, with all fitting parameters free and without excluding the data points closer to T_c. As it may be seen, the agreement is good in the region surely affected by T_c inhomogeneities but worse at higher ε [21]. Moreover, the fitting parameters present unreasonable values: $\Lambda = 0.026$ is anomalously smaller than unity and the ε onset of the critical fluctuation region ($\Gamma = 0.21$) is one order of magnitude larger than in the literature [11,23].

It is finally worth noting that the T' value proposed in Ref. [1] agrees, well within the experimental uncertainties, with the onset of the predicted field effects on the paraconductivity at 16 T (see Fig. 1). The implications of the precise location of T_{onset}, in particular in relation to the so-called pseudogap temperature, is still at present a debated central aspect of the phenomenological descriptions of the superconducting transition in HTSCs (comments on this issue may be seen in Secs. 5.2 and 5.3 of Ref. [5] and also in Refs. [7,8] and references therein).

In conclusion, some of the interesting microwave absorption measurements of Ref. [1] in a overdoped YBCO sample have been explained quantitatively and consistently with high-quality DC measurements in similar samples, on the grounds of the GGL approach for conventional superconducting fluctuations. In particular, our results confirm that the reduced-temperature range of the superconducting fluctuations above T_c extends well beyond the one proposed in Ref. [1], almost one order of magnitude in the case of the overdoped YBCO sample. These conclusions also concern several of the proposals, in some cases contradictory, of Refs. [7–9] and enhance the interest of extending to other HTSCs and to other observables quantitative analysis on the grounds of the GGL scenario.

Note added in proof. Two other references are relevant to this discussion [24,25].

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[20] As it may be seen in Figs. 7–9 of Ref. [1], the imaginary part of the complex conductivity (σ_2) decays much faster with ε than the real one (σ_1). This makes σ_2 more strongly affected by T_c inhomogeneities, which are expected to extend up to $\varepsilon \approx \Delta T_c/T_c \approx 0.02$ in sample OD89. Moreover, the negligibly small values of σ_2 at high ε makes it difficult to reliably detect the fluctuations onset. Finally, σ_1 may be more easily compared with the DC conductivity, a crucial check of consistency.

[21] Following the ΔT_c value in Table I of Ref. [1] for the sample OD89, the T_c inhomogeneities are expected to affect appreciably the σ_{1ab} data at reduced temperatures below 2×10^{-2}, where our fitting gets worse. In contrast, this is the reduced-temperature region where the fitting of Grbić *et al.* seems to be better. One may argue that the transition width is due to critical fluctuations, but for this analysis (down to $\varepsilon = 2 \times 10^{-3}$) to be consistent, the T_c distribution should be $2 \times 10^{-3} T_c = 0.18$ K wide or less. This is improbable, taking into account the nonstoichiometric nature of these compounds and the T_c dependence on the doping level [see e.g., J. Mosqueira, L. Cabo, and F. Vidal, Structural and T_c inhomogeneities inherent to doping in $La_{2-x}Sr_xCuO_4$ superconductors and their effects on the precursor diamagnetism, Phys. Rev. B **80**, 214527 (2009)].

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