Reply to “Comment on ‘Temperature range of superconducting fluctuations above Tc in YBa2Cu3O7−δ single crystals' ”

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

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In a previous article [M. S. Grbić *et al.*, Phys. Rev. B **83**, 144508 (2011)] we reported data on the high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ collected by a contactless microwave absorption technique, which provided evidence for superconducting correlations over a limited temperature range (10–20 K above T_c). The paraconductivity signal was determined by subtraction of zero-magnetic-field data from 16-T data. In the preceding Comment [D. Sóñora *et al.*, preceding Comment, Phys. Rev. B **102**, 176501 (2020)] D. Sóñora *et al.* argue that a 16-T magnetic field is not enough to quench all superconducting fluctuations in the microwave spectral range above T_c. As is obvious from the experimental data presented here, as well as from the data shown in the original paper, such conclusions disagree with our experimental results. Moreover, our initial experimental findings recently received independent robust confirmation from several different experimental techniques.

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In the preceding Comment [1], Sóñora *et al.* challenge our study of paraconductivity in cuprates [2]. Here we will additionally explain our experimental procedure and show that their reasoning is inconsistent with the presented experimental data.

As the authors of the preceding Comment [1] correctly pointed out, the appearance of superconductivity in cuprates is a vividly discussed topic from the discovery of the high-T_c phenomenon. Numerous, often mutually exclusive, scenarios were proposed stemming from uncertainties related to a correct separation of normal-state properties from those related to superconductivity. Essentially, nine years ago, there were two procedures for extracting the superconducting contribution to the measured data. The first procedure involves a fit of normal-state properties by some, in principle arbitrary, function specific for every experimental technique (e.g., resistivity and susceptibility). The deviations from this assumed curvature would be attributed to the appearance of superconductivity. Such procedures have regularly led to quite different results, depending on the choice of the assumed background, adding to the controversy in cuprates. Notably, such a procedure, when applied away from T_c, leads to large uncertainties since, with increasing temperature, the superconducting signal is much smaller than the assumed normal-state one. Another approach was to use a magnetic field to suppress the superconductivity and its traces above T_c. Consequently, the difference between the zero-field and high-magnetic-field measurement above T_c is attributed to superconductivity. It is expected that magnetic field and temperature in close association destroy the superconducting properties, and thus this method seems to be reliable away from T_c.

In 2011 we applied the latter procedure to extract the paraconductivity contribution above the superconducting critical temperature T_c in the reported microwave absorption measurements [2]. The highest applied field was 16 T. Measurements were performed on deeply underdoped, slightly underdoped, and overdoped $YBa_2Cu_3O_{7-\delta}$ single crystals. The temperature range of the precursor superconducting regime ($T' - T_c$) was thus determined by an experimental method free from arbitrary assumptions about subtracting the nonsuperconducting contributions to the total measured signal and/or theoretical models to extract the unknown parameters. The paraconductivities were detected in the *ab*-plane and *c*-axis conductivity. Within the sensitivity of the method, the precursor regime is found only within a fairly narrow temperature range above T_c (10–20 K). It is also worth mentioning that a similar study was conducted on an Hg1201 single crystal, yielding a similar result [3].

In the preceding Comment [1] Sóñora *et al.* argue that a 16-T magnetic field is not strong enough to quench superconducting correlations above T_c in $YBa_2Cu_3O_{7-\delta}$. Starting from here, they conclude that the temperature T' identified from microwave absorption measurements is a serious underestimation and the actual onset of the precursor superconductivity is in fact located well above (an order of magnitude) T'. Here we will show that the conclusions of the preceding Comment do not follow from (our) experimental data. Although this is already evident from our initial paper [2], here we provide

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additional data, which demonstrate that the traces of superconductivity can be observed in our microwave data only in a rather narrow temperature range above T_c. Importantly, this conclusion stems directly from the experimental data and is completely model or assumption independent.

The main experimental observation (Fig. 6 of Ref. [2]) is that upon increasing the temperature, starting from the temperatures that are several degrees kelvin above T_c, there are no measurable differences (within the precision of the measurement, 0.1 ppm) between data collected at 8 T and those collected at higher fields (up to 16 T). Thus, we have concluded that the 16-T curve is a good measurement of the normal-state absorption in this temperature range. The saturation of the conductivity by the magnetic field is also evident from the microwave absorption as-measured data (model and assumption free) shown in Fig. 1. Clearly, there is no difference (within the experimental limit of 0.1 ppm) between the measured microwave absorption in $B = 12$ T and in $B = 16$ T for the temperatures that are higher than 91 K [up to room temperature (not shown)]. It is worth noting that the same criterion was used in the pioneering work of Tinkham and co-workers [4,5], evoked by the authors of the preceding Comment [1], for the determination of zero magnetization (background) in their experiments. In other words, Fig. 1 clearly shows that a 12 T magnetic field is large enough to quench the superconducting correlations at all reduced temperatures above $\varepsilon = 0.02$, i.e., above 91 K. Hence, following the criterion of Ref. [1], our procedure is adequate for the determination of T', as long as it lies above 91 K. Consequently, based on this argument, we can only conclude that the fields applied indeed reveal the normal-state conductivity suitable for the background subtraction (in the temperature range of interest, i.e., above 91 K).

In this respect, we would also like to caution that, as clearly stated in [2], our discussion and main results are based on zero-field data, which show the appearance of enhanced conductivity only in a narrow regime above T_c. Away from T_c, as we clearly demonstrate here and in our initial paper, this background could have been equally well determined at 8 T (as shown in Fig. 6 of [2]), 12 T, or 16 T, or any stronger field (if available), since no field dependence (to the precision of the measurement) was observed. Thus, there is no point to try to interpret [1] our results in terms of the finite-field effects similar to those described in the contributions of Tinkham and co-workers [4,5]. Moreover, the claim that we have determined the real part of the total in-plane AC magnetoconductivity at 16 T [1] is incorrect. In that sense, the definition of $T'(16\text{ T})$ in Eq. (1) of the preceding Comment [1] is misleading. The authors could have equally well have chosen to define $T'(12\text{ T})$, $T'(8\text{ T})$, or any other higher field [e.g., $T'(50\text{ T})$] and the result would be always the same. Hence, the discussion that follows in the preceding Comment and the related conclusions are erroneous.

Finally, we would like to emphasize that recent experimental developments support our conclusions. In particular, the nonlinear conductivity that does not require any background subtraction [6], as well as shot-noise measurements [7], also identified traces of superconductivity only in a narrow temperature region (20–30 K) above T_c. Moreover, it appears that this regime is essentially doping and compound independent

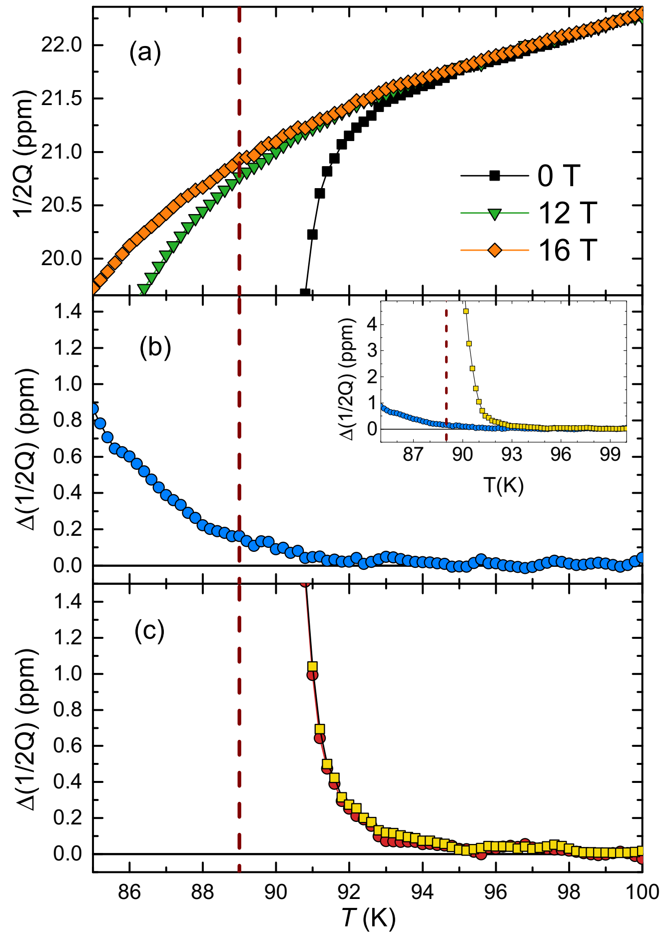

FIG. 1. (a) As-measured microwave absorption in overdoped YBCO ($T_c = 89$ K) in zero field (black squares) and in magnetic fields of $B_{\mathrm{DC}} = 12$ T (green triangles) and 16 T (orange diamonds) applied parallel to the c axis, presented in the temperature range of interest. Induced microwave currents are flowing partly along the a axis and partly along the c axis. Clearly, the high-field curves are overlapping for $T > 91$ K. This experimental fact is furthermore visualized by depicting the difference between microwave absorption at 16 and 12 T in (b). Clearly, this difference falls below our experimental limit (0.1 ppm) above 91 K. Hence, both high-field data can be used as background for $T > 91$ K. The inset compares the difference from the main panel (blue circles) with the difference between microwave absorption in 16 and 0 T (yellow squares), showing that the zero-field paraconductivity is substantially larger than the background uncertainty several kelvin above T_c. (c) Zero-field absorption from which both backgrounds (12 T shown as red circles and 16 T shown as yellow squares) are subtracted. The estimation of the paraconductivity regime does not depend on the field in which the background is measured.

[6]. Thus, one can conclude with confidence that our approach in 2011 was proper and that our estimation of the limited temperature range of superconducting precursor in microwave conductivity data was correct. We reiterate [2] that our measurements alone do not preclude superconducting fluctuations with frequencies outside the microwave window at elevated temperatures.

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