Comment on "Microwave vortex dissipation of superconducting Nd-Ce-Cu-O epitaxial films in high magnetic fields"

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Experimental and theoretical results contained in a paper and in an Erratum by Yeh *et al.* [Phys. Rev. B **48**, 9861 (1993); Phys. Rev. B **56**, 5683(E) (1997)] discussing experiments employing a novel sapphire ring resonator to investigate microwave frequency vortex dissipation in thin film $Nd_{1.85}Ce_{0.15}CuO_x$ as a function of applied field and temperature are discussed. These authors also claim to have extended the Coffey-Clem [Phys. Rev. Lett. **67**, 386 (1991); Physica C **185-189**, 1915 (1991); Phys. Rev. B **45**, 10527 (1992)] model to include thin-films. The authors' theoretical results for the surface resistance as a function of applied field and temperature, which as illustrated in their paper were in *detailed* agreement with the data, are *only approximately* able to describe the data by scaling the theoretical expressions by unspecified multiplicative factors ~50. The given theory contains no free scaling parameter. In the Erratum, the theory is still in detailed agreement with the NdCe214 data, although these data have changed by roughly a factor of ~1/50 due to a claimed *experimental* recalibration. No explanation was offered to account for the change in the theory, by ~1/50. In addition, the expressions provided for the surface resistance are not correct with obvious nonphysical limits: for example, the normal state surface *resistance* is independent of the *resistivity*. The *recalibrated data* are inconsistent with published results for the surface resistance for superconductors and thin film conductors. Equations for the $B=0$ surface resistance treatment, purportedly appropriate to a finite grain-size limit, were dimensionally inconsistent in the original paper, and an associated fitting parameter was not specified. A value for this "missing" parameter was given in the Erratum, but evaluation of the revised $B=0$ surface resistance expression with this parameter *fails even to approximate* the published $B=0$ curves. Several results from the work of others were misquoted.

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1. The data in Figs. 2(a) and 2(b) of Ref. 1 were not described by the several equations using the given parameters; the computed results are smaller than the data by a factor of approximately 56 at 12.34 GHz, and 47 at 18.289 GHz. Nevertheless, the computed results for $B>0$ presented by Yeh *et al.* in their Fig. 2 *appear* to *accurately* describe the data over the full temperature range. In the Erratum, the authors fail to either explain or to even acknowledge the original scaling of the theory; instead, the data in their Fig. 2 (Ref. 2) now appear to closely match their erroneous (unscaled) theory which has nonphysical limits. In other words, the data and the results of evaluation of the theory expressions have *both* changed, by factors of ~1/50 and appear to coincide with the unscaled "theory." However, the data for a Y123 film included as an inset to their Fig. 1 (Refs. 1 and 2) have not changed. This seems to imply that the "correct" calibration factors were known prior to publication of the Erratum. In the Erratum, no explanation was offered which could account for the change in the theory in their Fig. 2. Further, no explanation for the two changes in experimental calibration were offered, or why the data for the Y123 film remain *unchanged*. From the results of paragraph 3 below, it is impossible that an *independent* recalibration of their instrument could yield such results.

2. The authors indicate that one of the frequency independent parameters, $K_\rho(0)$, was "adjusted" to fit the data from the two different frequencies, this is an apparent direct contradiction to a claim also made by the authors who wrote, "We note that these curves are obtained by *simultaneously* fitting all isotherms (over 500 data points) with the same set of parameters." The fitting parameters, claimed to result from the nonlinear least-squares fitting to the data, are surprisingly *whole numbers*, with no decimal fractions; this is statistically quite improbable. The authors make no use of approximate signs to suggest that these parameters have been approximated or truncated. In addition, the paper contains neither a statement of the goodness of fit parameter, χ^2, nor uncertainties for the several parameters. Evaluation of the theoretical $B>0$ expressions with the given parameters *fails to yield any of the thirteen published curves* for the two frequencies, see this Comment Fig. 1.

3. In the limit as $T\rightarrow T_C$ both of the authors' surface resistance expressions [Eqs. (5) and (8)] reduce to $R_s=\mu_0\omega d$. Here ω is the microwave angular frequency, d is the film sample thickness (1.3×10^{-7} m), and μ_0 is $4\pi\times10^{-7}$ H/m. At 12.34 GHz this is ~12.66 mΩ, while at 18.289 GHz the result is ~18.77 mΩ. These data can also be compared to published temperature-dependent surface resistance data on a high quality $Pr_{1.85}Ce_{0.15}CuO_{4-d}$ crystal.[6] In this case, R_s at ~1.2 K in the *superconducting* state and a lower frequency of 9.6 GHz is larger, ~25 mΩ, than the (*recalibrated*) Yeh *et al.* data in the *normal* state. At low temperatures, the data of Fig. 2 (Ref. 2) are now ~0.25 mΩ at 12.34 GHz. The point is that if the authors' theory were correct, the normal state

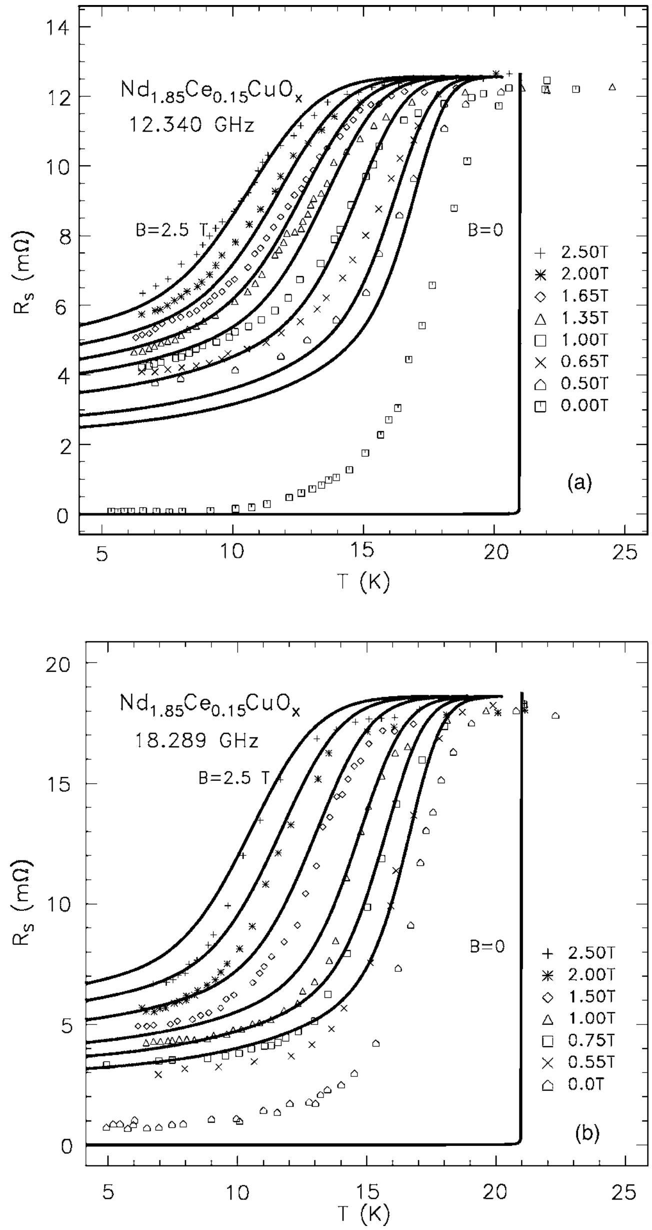

FIG. 1. Surface resistance data from the Erratum, as compared to data in Ref. 1, they are divided by ~56 for 12.340 GHz (a), and ~47 for 18.289 GHz (b) to approximately match the erroneous normal limit of the theory are plotted along with evaluation of Eq. (5) for $B>0$, and Eq. (8) (as corrected in the Erratum) for $B=0$ using the authors' specified parameters. The field values vary from 0 to 2.5 T, as specified in Ref. 1. For each frequency, the $B=0$ "fit" results fall rapidly to $R_s \cong 0$ just below T_c. These calculations fail to reproduce the results of Fig. 2 of Ref. 2.

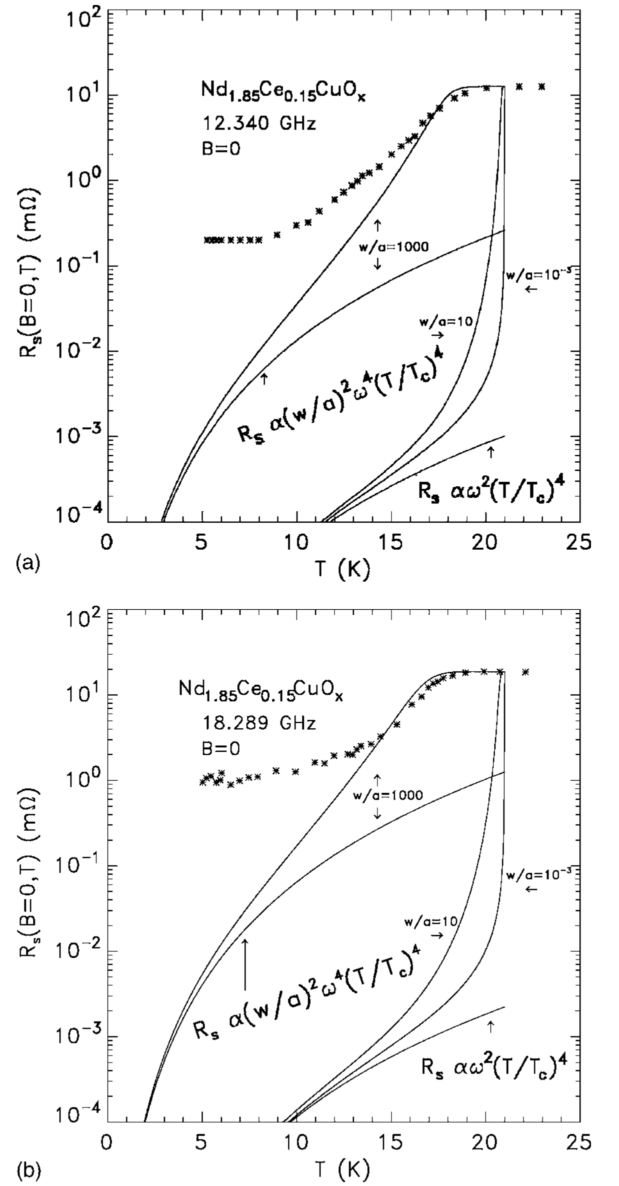

FIG. 2. The data of Yeh *et al.* Fig. 2 (Ref. 2) for $B=0$ and 12.340 GHz (a) and 18.289 GHz (b) are here replotted along with three "fits" to these data using $w/a=1\times10^{-3}$, 10, and 1000, right to left, respectively. In addition, the approximations for R_s for small and large w/a which vary as $(T/T_c)^4$ are shown. These results are presented as a semilog plot, in order to illustrate how different the fitting function is from the data. The curve with the nonphysical value for $w/a=1000$ is the closest to the data, but falls off at low temperatures much more rapidly than does the authors' curves which closely match the data. In this limit, R_s varies as ω^4, not as ω^2, as claimed by the authors. Near the transition temperature, using the authors' given value for $w/a=1\times10^{-3}$, the surface resistance curve falls abruptly to a very small value.

surface resistance would be independent of the resistivity; films sufficiently thin made of *anything* (*even vacuum*) would be superior to the *best* thicker superconducting films, and for example, (insulating) electrical tape would actually be highly conductive at 60 Hz, and *perfectly conductive* at dc. Because the authors' model is incorrect, and independent of the *resistivity*, using samples of different thicknesses cannot yield a valid calibration (or recalibration).

4. Excluding substrate effects, the normal state surface resistance for a thin film is[7]

$$R_S = \frac{\rho}{\delta}\left[\frac{\sinh\left(\frac{2d}{\delta}\right)+\sin\left(\frac{2d}{\delta}\right)}{\cosh\left(\frac{2d}{\delta}\right)-\cos\left(\frac{2d}{\delta}\right)}\right].$$

In the limit for which the rf skin depth δ is much smaller than the film thickness d, $R_S=\rho/\delta$ where ρ is the resistivity, giving $R_s=(\mu_0\omega\rho/2)^{1/2}$. In the limit as $\delta \gg d$, $R_S=\rho/d$, which is independent of the *frequency*, not the *resistivity*. The limiting results derived from the above equation can also be obtained by a simple argument. Consider a rectangular parallelepiped having a resistivity ρ of dimensions $l\times l\times d$, where d is the slab thickness. If a uniform current is carried in the cross-sectional area $a=d\times l$, the resistance is $R=\rho l/a=\rho l/(dl)=\rho/d$. If the current instead is carried in a cross-sectional area $l\delta$, the resistance is $R=\rho/\delta$.

Under particular circumstances, impedance match to the substrate should also be considered, as illustrated by Drabeck *et al.*[8,9] for cavity measurements. For extremely thin films, radiative losses through the film are important. This has been discussed in some detail by Sridhar,[10] and illustrated through detailed measurements. Coffey and Clem[11] provide analysis of a noncavity measurements; the dissipative losses they compute have the same general dependence on the film thickness as given here, except for films of a few angstroms thickness. In general, as $d\to 0$, the ohmic losses vanish as $R_S\to\infty$, and the incident power is transmitted. In the author's apparatus, transmitted power is *not* equivalent to dissipated power. For a clear demonstration that the surface resistance of a bulk HTSC for $B=0$, near the transition temperature is very well approximated by using the dc resistivity $\rho(T)$ in the classical surface resistance expression, see Bonn *et al.*[12] Fig. 1.

At 12.34 GHz with the given normal state resistivity, $\rho_n=1.9$ mΩ, the skin depth is 19.7 μm which is much greater than the thickness of the sample (0.13 μm). Accordingly, the normal state surface resistance is well approximated by $R_s=\rho_n/d\cong 146.2\ \Omega$ and nearly frequency independent, not ~12.5 mΩ at 12.34 GHz or ~18.2 mΩ at 18.289 GHz as given in the Erratum. Applying the author's model, gives 12.66 mΩ at 12.34 GHz and 18.77 mΩ at 18.289 GHz. That is, the (theory) results given by the authors in their Erratum are in error by a factor of roughly 10^4, *and do not even agree precisely with their erroneous model*.

5. The authors emphasized that for $B=0$, their expression for R_S is a function of only *one* parameter, the ratio w/a *which was not originally specified* (a is the diameter of a grain, and w is the width of a junction connecting grains). In their Erratum, the authors present an equation which is dimensionally correct, and a value for the missing parameter, $w/a=10^{-3}$. The value given for this parameter fails to yield a curve *even approximating* the results in either the paper or the Erratum. Attempting to use the given equation with a value for $w/a=1000$ only approximately reproduces the results included in Fig. 2 (Refs. 1 and 2); a value for $w/a>1$ is nonphysical. Even with a nonphysical value for w/a, the modeled results differ from the scaled results given in Ref. 1, or in the Erratum. With the claimed sensitivity of 10 $\mu\Omega$ (10^{-2} mΩ), it should have been easy to demonstrate the validity of their $B=0$ equations; see this Comment Fig. 2.

6. Yeh *et al.*[1] wrote, "Note that the zero-field surface resistance (R_s) increases with the increasing frequency f and that $R_s\propto f^\alpha$, with $\alpha\approx 2.0$ at $T\ll T_c$, consistent with conventional theories." The $B=0$ expression (with $\omega=2\pi f$) was

$$R_S = \frac{\mu_0\omega d}{\sqrt{1+\dfrac{\rho_n^2T_c^8(1-T^4/T_c^4)^2}{\mu_0^2\omega^2T^8\lambda_0^4\left(1+\dfrac{\hbar^2\omega^2w^2}{1.76^2k_B^2T_c^2a^2(1-T/T_c)\tanh\left(\dfrac{1.76T_c\sqrt{1-T/T_c}}{2T}\right)^2}\right)}}}.$$

Below the transition temperature at ~19 K and 12.34 GHz, the revised datum is ~10 mΩ, while the $B=0$ expression with $w/a=10^{-3}$ evaluates to ~2.1 $\mu\Omega$. For this and lower temperatures, the theoretical curve is nearly four orders of magnitude smaller than the data, and the curve drawn by the authors which closely approximates the data. In the limit as $T\ll T_c$, and $w/a\ll 1$, the above expression approximates to

$$R_s \cong \left(\frac{d}{\rho_n}\right)(\mu_0\lambda_0)^2\left(\frac{T}{T_c}\right)^4\omega^2,$$

confirming the claim for the frequency dependence, but showing that the surface resistance varies rapidly with temperature approximately as $(T/T_c)^4$, and vanishes at $T=0$, quite unlike the authors' model plot for either frequency. This approximate expression is also independent of w/a. If, instead, a large nonphysical value is used for w/a and $T\ll T_c$, the surface resistance retains the temperature dependence given above, but varies as

$$R_S \cong \frac{d}{\rho_n}\left(\frac{\mu_0\hbar\lambda_0}{1.76k_BT_c}\right)^2\left(\frac{w}{a}\right)^2\left(\frac{T}{T_c}\right)^4\omega^4.$$

The authors' *nonreproducible* fits to the data for $B=0$ closely match the data in Fig. 2(a) (Refs. 1 and 2) while their fit falls *below* the 18.289 GHz data in Fig. 2(b) (Refs. 1 and 2). It is

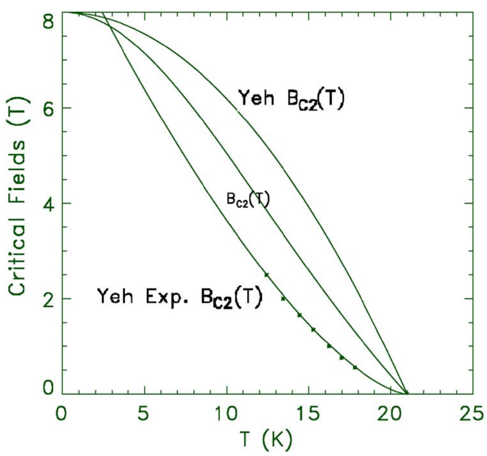

FIG. 3. (Color online) Data from Fig. 3 of Ref. 1 for $B_{C2}(T)$ is illustrated along with the function used by the authors for $B_{C2}(T)$, and the more familiar function expected for the temperature dependence of $B_{C2}(T)$ as given by Coffey and Clem. The so-called $B_{C2}(T)$ data fit nicely on a curve which has the temperature dependence as actually given (as opposed to the dependence quoted by the authors) by Tinkham for the barrier height, $(1-T/T_C)^{3/2}$.

not possible to draw such fits with the given equations, and any value for *w/a,* see this Comment Fig. 2. What is even more difficult to understand are the data at ~5 K, with $B > 0$, which for the same fields, are consistently smaller at the higher frequency than the lower frequency.

7. In Fig. 3 of Ref. 1, the "experimental" B_{C2} curve is plotted as a function of temperature. This curve is very different from the expression used by the authors in their model, see this Comment Fig. 3. It would be useful to understand, since the data are so different from the modeled temperature dependence, why the model was employed. The procedure used by the authors, if it were reliable, should have *confirmed* the value for B_{C20} found by fitting; it did not. The value determined for B_{C20} is surprisingly small; one may have expected a value nearer 40 T, than 8 T.

8. Since the authors claim to have made a "thin-film" extension of the Coffey-Clem model,[3–5] it comes as a surprise that there are *unrelated* changes to that model. For example, the function employed to describe the temperature dependence of B_{C2} is not the function previously given by Coffey and Clem.[3–5] This is not the only unspecified modification. In Ref. 1, the authors assert that Tinkham gave a function for the barrier height U_p which they claim varies with temperature as $[1-(T/T_C)^2]^{3/2}$. In fact, Tinkham's temperature dependence was given as $(1-T/T_C)^{3/2}$. Ironically, the Tinkham temperature dependence emerges from the authors claimed measurement of B_{C2}, see this Comment Fig. 3. Further, the Coffey-Clem model for the pinning force constant has no dependence on the applied field; the expression given by the authors varies with field as $B^{-1/2}$. No motivation was provided for these several extensions; *more importantly, the incorrect attributions were not identified*.

Three different "recalibration factors" were employed in the Erratum (~1/56 at 12.34 GHz, and ~1/47 at 18.289 GHz for the NdCe214 film, and 1 for the Y123 film), not one as claimed by the authors. Since there is no evidence for a reliable (if any) calibration procedure, there is no reason to have any confidence that the (*whole number*) parameters obtained from the least-squares fitting and given without any estimate of uncertainty, are of any physical relevance.

Further, there is no reason to conclude that the novel dielectric ring resonator measurement technology employed represents an advance over more conventional techniques. Finally, one could have reasonably expected that the coauthors would have noticed at least some of these several difficulties, if not in the paper, at least in the Erratum.

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[1] N.-C. Yeh, U. Kriplani, W. Jiang, D. S. Reed, D. M. Strayer, J. B. Barner, B. D. Hunt, M. C. Foote, R. P. Vasquez, A. Gupta, and A. Kussmaul, Phys. Rev. B **48**, 9861 (1993).
[2] N.-C. Yeh, U. Kriplani, W. Jiang, D. S. Reed, D. M. Strayer, J. B. Barner, B. D. Hunt, M. C. Foote, R. P. Vasquez, A. Gupta, and A. Kussmaul, Phys. Rev. B **56**, 5683(E) (1997).
[3] M. W. Coffey and J. R. Clem, Phys. Rev. Lett. **67**, 386 (1991).
[4] J. R. Clem and M. W. Coffey, Physica C **185-189**, 1915 (1991).
[5] M. W. Coffey and J. R. Clem, Phys. Rev. B **45**, 10527 (1992).
[6] J. D. Kokales, P. Fournier, L. V. Mercaldo, V. V. Talanov, R. L. Greene, and S. M. Anlage, Phys. Rev. Lett. **85**, 3696 (2000).
[7] S. Ramo and J. Whinnery, *Fields and Waves in Modern Radio* (Wiley, New York, 1944), p. 217; S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics* (Wiley & Sons, Inc., New York, 1965), p. 301.
[8] L. Drabeck, K. Holczer, G. Grüner, and D. J. Scalapino, J. Appl. Phys. **68**, 892 (1990).
[9] L. Drabeck, K. Holczer, G. Grüner, J.-J. Chang, D. J. Scalapino, A. Inam, X. D. Wu, L. Nazar, and T. Venkatesan, Phys. Rev. B **42**, 10020 (1990).
[10] S. Sridhar, J. Appl. Phys. **63**, 159 (1988).
[11] M. W. Coffey and J. R. Clem, Phys. Rev. B **48**, 342 (1993).
[12] D. A. Bonn, R. Liang, T. M. Riseman, D. J. Baar, D. C. Morgan, K. Zhang, P. Dosanjh, T. L. Duty, A. MacFarlane, G. D. Morris, J. H. Brewer, W. N. Hardy, C. Kallin, and A. J. Berlinsky, Phys. Rev. B **47**, 11314 (1993).