Fluctuations in the microwave conductivity of $YBa_2Cu_3O_{7-\delta}$ single crystals in zero dc magnetic field

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We present a quantitative analysis of finite frequency fluctuation conductivity above and below T_c in cuprate superconductors in zero dc magnetic field. In a $YBa_2Cu_3O_{7-\delta}$ crystal showing a linear in temperature increase of the penetration depth at low temperatures, we find that two-dimensional (2D) finite frequency Gaussian conductivity fluctuations above T_c cross over into a slower divergence of the conductivity as T_c is approached from above. We find that the critical regime above T_c is less than about 0.6 K wide. At and below T_c, 3D fluctuations dominate the conductivity, with evidence of 3D *XY* critical scaling of the imaginary part of the conductivity down to 5 K below T_c.

Cuprate superconductors differ from their low-temperature counterparts in a number of significant and dramatic ways. Their small superconducting coherence length, reduced dimensionality imposed by the CuO_2 planes, low carrier density and high transition temperature lead to situations where superconductivity can be strongly affected by the large thermal energies available. The cuprates offer the opportunity to establish the nature and universality class of superconducting fluctuations.

It has been known for some time that the normal state dc conductivity of the cuprates is strongly enhanced well above the thermodynamic transition temperature, T_c.[1,2] Specific heat measurements on highly homogeneous single crystals show evidence of a peak at T_c, where BCS (mean field) theory says that only a discontinuity should appear.[2] The resemblance of this peak to the lambda transition in superfluid ^{4}He suggests that the cuprates may be in the same universality class, namely that of the three-dimensional (3D) *XY* model. Recently, experimental evidence obtained from rf penetration depth measurements also suggests that 3D *XY* critical fluctuations exist down to 9 K below T_c.[3]

In this paper we shall examine the microwave conductivity in the normal state to identify further evidence for enhanced fluctuations in the cuprates. We shall focus on microwave surface impedance measurements on a high quality single crystal of $YBa_2Cu_3O_{7-\delta}$ (YBCO) which shows a linear-in-T increase of the penetration depth at low temperatures,[4] and 3D *XY* critical behavior just *below* T_c. We find that this crystal has no corresponding range of critical fluctuations in the microwave conductivity *above* T_c.

Growth and characterization of the YBCO crystals has been discussed in detail elsewhere.[4,5] The twinned YBCO crystals ($\sim$1 mm$\times$1 mm$\times$30–50 μm) typically show zero dc resistance at 92–93 K, with a normal state resistivity at 100 K of about 40–50 $\mu\Omega$ cm, similar to that of the Illinois crystals.[6] ac- and dc-magnetization measurements also confirm the transition temperature to be 92–93 K with the transition width approximately 0.2 K. Although several crystals were measured for this work, we shall concentrate on the analysis of the crystal showing the greatest degree of homogeneity in surface impedance measurements.

The surface impedance measurements were made by a cavity perturbation method which is discussed elsewhere.[4,5,7] Briefly, the surface resistance $R_s(T)$ and change in surface reactance $\Delta X_s(T)$ of the samples are measured *simultaneously*, from 4.2 K *continuously* up to well above T_c. As a key step in the analysis of the data, we convert $\Delta X_s(T)$ into an absolute magnitude: $X_s(T)$, following the method of Refs. 4 and 5. We then determine the full complex conductivity $\sigma=\sigma_1-i\sigma_2$, from the definition $R_s+iX_s=[i\omega\mu_0/(\sigma_1-i\sigma_2)]^{1/2}$ in the local limit. Note that the data used in this paper has no contribution from shielding currents which flow in the c direction[4] (unlike Ref. 3), and that no residual resistance is subtracted from R_{s-ab} before calculating σ_1.

The inset of Fig. 1 shows results for the temperature dependence of the penetration depth and conductivity σ_1 of a single crystal of YBCO. The magnetic penetration depth, λ ($X_s=\mu_0\omega\lambda$), increases from its low temperature value lin-

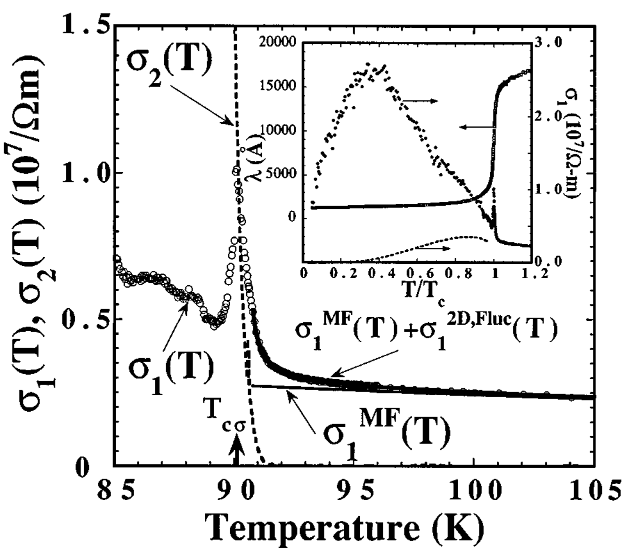

FIG. 1. Complex conductivity, $\sigma_1(T)$ (circles), $\sigma_2(T)$ (dashed line) in the vicinity of T_c of a YBCO crystal at 9.6 GHz, along with 2D fit mean field and total conductivities (solid line) above T_c. Inset shows the penetration depth and $\sigma_1(T)$ over the temperature range from 4.2 to 110 K, as well as the BCS $\sigma_1(T)$ (dashed line).

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TABLE I. Results of fits to the 9.6 GHz conductivity above T_c [for $(T-T_{c\sigma})/T_{c\sigma}>0.008$] to the 2D, 3D, and Klemm fluctuation models. Also shown are LD fits to dc fluctuation conductivity (Hagen and Friedmann). T_{c0} is the zero dc resistance T_c.

Fit	b ($\mu\Omega$ cm/K)	ρ_0 ($\mu\Omega$ cm)	t (Å)	ξ_0 (Å)	s (Å)	$\xi_0(6\pi m/M)^{1/2}$ (Å)	T_c (K)	$\chi^2/\chi^2_{\min}$
2D[b]	0.479	−6.79	16.3				90.473	1
2D	0.204	22.4	8.24				90.114[a]	13.9
3D[b]	0.318	15.2		0.637			90.660	2.5
3D	1.24	−82.8		8.0[a]			90.796	180
3D	0.007	58.0		0.32			90.114[a]	44
Klemm[b]	0.479	−6.86			16.3	0.0085	90.473	1
Klemm[b]	0.473	−6.19			15.7	0.85[a]	90.571	1.08
Klemm	0.339	9.49			8.47	0.016	90.114[a]	15.4
Hagen *et al.* (Ref. 14)	0.42	5.4			6	1–1.7	3–5 K below T_{c0} (fit for $\varepsilon>0.06$)	
Friedmann *et al.* (Ref. 6)	0.8	14			1.71	0.435	2.5 K below T_{c0} (fit for $\varepsilon>0.058$)	

[a]Denotes parameter constrained to this value in the fit.
[b]Denotes fit shown in Fig. 2.

early with temperature, with a slope of approximately 5 Å/K for 5 K$<T<$35 K.[4,5,8] As T_c is approached from below, the penetration depth increases very abruptly, suggestive of unconventional behavior. On the other hand, as T_c is approached from above, $\sigma_1(T)$ is considerably enhanced, showing a sharp peak in the vicinity of T_c at a temperature we define as $T_{c\sigma}$ (see Fig. 1). This enhancement of $\sigma_1(T)$ near T_c in microwave measurements of YBCO has been noted before[4,9–11] but has not yet received a detailed analysis. When the same measurements are done on a Nb crystal, no enhancement of $\sigma_1(T)$ above T_c is seen, and there is no peak at T_c, although a BCS coherence peak is observed at lower temperatures[5,12] (similar to the dashed line in the inset of Fig. 1).

When analyzing the data above T_c shown in Fig. 1, one makes the assumption that the total conductivity is the sum: $\sigma_1(T,\omega)=\sigma_1^{\mathrm{MF}}(T)+\sigma_1^{\mathrm{fluc}}(T,\omega)$, where $\sigma_1^{\mathrm{MF}}(T)=1/(\rho_0+bT)$ is the "mean field" conductivity ($T>T_c$), which we take to be frequency independent, and σ_1^{fluc} is due to superconducting fluctuations above T_c. Far above T_c, the fluctuation contribution to σ_1 should be small, and fits to $\sigma_1(T)$ for 100 K$<T<$150 K (Ref. 13) give $\rho(T)\approx-6.8$ $\mu\Omega$ cm$+0.47$ ($\mu\Omega$ cm/K)T, which is consistent with the measured dc resistivity of crystals from the same batch. The enhanced conductivity above T_c has been measured by many groups at dc,[6,14] and a summary of their best fit results is given in Table I. The mean field T_c values of all these dc fits are several kelvin below the measured zero resistance temperature. This is manifested in the data by a conductivity which diverges more quickly than the theoretical predictions as T_c is approached from above.[6] As a result, the dc data is only fit relatively far above the transition, excluding a great deal of potentially important data near the transition. However, because the dc data was fit up to 200 K,[6] their conclusions about the nature of the fluctuations far from T_c are stronger than ours. Our finite frequency $\sigma(T,\omega)$ measurements complement the dc measurements because they have one important advantage. According to theory, $\sigma_1^{\mathrm{fluc}}(T,\omega>0)$ does not diverge at T_c as in the dc case, but approaches a finite value which decreases with increasing frequency.[15,16] One consequence of this is the fact that we can measure $\sigma_1(T)$ right through T_c, a feat which is impossible with dc measurements. Hence our measurements are better suited to examine the region near T_c where critical fluctuations are expected.

Another important advantage of microwave measurements is their sensitivity to multiple superconducting transitions. dc resistance measurements are sensitive only to the first percolating path through the sample, so that other regions with significantly reduced T_c can coexist in the sample and remain undetected. The microwave measurements are very demanding of sample homogeneity (at least within a skin depth of the surface), and we have selected a sample to discuss in detail which shows the greatest degree of homogeneity in the temperature dependent surface impedance.

To our knowledge, only two previous quantitative measurements of finite frequency fluctuation conductivity in zero dc magnetic field have been made, both on ultra-thin Pb films.[17,18] It was found in both those measurements that a time-dependent Ginzburg-Landau (TDGL) theory[15] of finite frequency Gaussian fluctuation conductivity was successful in treating that data. In that theory, the fluctuation conductivity depends on the dimensionality, d, of the system:[15] $\sigma_1^{\mathrm{2D,fluc}}(T,\omega)=(\sigma_1^{\mathrm{2D,dc}}/\omega_0)\,[\pi-2\tan^{-1}(1/\omega_0)-(1/\omega_0)\ln(1+\omega_0^2)]$ for a film of thickness $t<\xi_c$ (the c-axis coherence length), or $\sigma_1^{\mathrm{3D,fluc}}(T,\omega)=[(8/3)\sigma_1^{\mathrm{3D,dc}}/\omega_0^2]\,[1-(1+\omega_0^2)^{3/4}\cos((3/2)\tan^{-1}(\omega_0))]$ for a bulk material, where $\sigma_1^{\mathrm{2D,dc}}=e^2/(16\hbar t\varepsilon)$ and $\sigma_1^{\mathrm{3D,dc}}=e^2/(32\hbar\xi_0\varepsilon^{1/2})$ are the well-known dc fluctuation conductivity expressions,[19] with ξ_0 the 3D coherence length at $T=0$, $\varepsilon=\ln(T/T_c)\approx T/T_c-1$, and $\omega_0\equiv\pi\hbar\omega/(16k_BT_c\varepsilon)$ is the dimensionless TDGL time scale. Because of the success with the Lawrence-Doniach (LD) model in fitting the dc fluctuation conductivity,[6] we also fit to

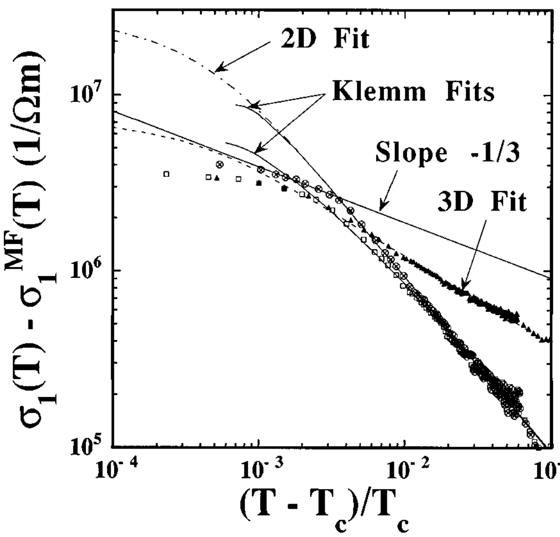

FIG. 2. Experimental and theoretical conductivity minus fit mean field conductivity, $\sigma_1(T)-\sigma_1^{\rm MF}(T)$ vs $\varepsilon \approx T/T_c - 1$ above T_c for a YBCO single crystal. Data minus fit mean field are shown as circles (2D), crosses (unconstrained Klemm), squares (constrained Klemm), and triangles (3D). The Klemm fits (solid, upper is unconstrained), 2D fit (dash-dot), and 3D fit (dashed) are shown as lines.

Klemm's finite frequency generalization of the LD model:[20] $\sigma_1^{\rm Klemm,fluc}(T,\omega)=(e^2/16\hbar s)/[\varepsilon(\varepsilon+\beta)]^{1/2}\{1-\omega_0^2[\varepsilon^2+\beta\varepsilon+(3/8)\beta^2]/[6(\varepsilon+\beta)^2]\}$ where s is the layer separation, $\beta=6\pi(\xi_0/s)^2(m/M)$ is the anisotropy parameter, with m/M the ratio of in-plane to perpendicular effective masses. In all fits, we ignore the Maki-Thompson correction, and do not attempt to fit $\sigma_1(T)$ below T_c at this time because the mean field theory for $\sigma_1(T)$ below T_c is considerably more complicated than that above T_c.

We have adopted the approach of Hagen *et al.*[14] in that we fit to the total conductivity data, rather than subtracting off a best guess for the mean field contribution and fitting the residual conductivity. Results of fits up to 110 K are shown in Table I and Fig. 2. The data and fits in Fig. 2 are presented with the fit mean field conductivity subtracted away. Note that each fit has a different T_c and a different mean field contribution to the total conductivity, so that even though all the fits were performed on the same $\sigma_1(T)$ data set, they appear to be different when presented as $\sigma_1(T)-\sigma_1^{\rm MF}(T)$ vs $(T-T_c)/T_c$ in Fig. 2.

The 3D fit parameters in Table I show poor agreement with independent rf and dc estimates of the mean field resistivity, casting doubt on the validity of the overall fit. Also, the fit 3D coherence length ξ_0 is unsatisfactorily small, and constrained fits with $\xi_0=(\xi_{ab}^2\xi_c)^{1/3}\sim 8$ Å, or $T_c=T_{c\sigma}$, were much worse (note the values of the mean field resistivity parameters, and the values of χ^2 in Table I). The 2D and Klemm fits give mean field parameters consistent with independent measurements and have the lowest χ^2 values. The unconstrained 2D and Klemm fits are virtually identical, since the small size of the "out-of-plane" coherence length (Ref. 20) $\xi_0(6\pi m/M)^{1/2}$ relative to the layer separation, s, indicates that a 2D to 3D crossover does not occur within the range of the experimental data for the Klemm fit. A constrained Klemm fit with $\xi_0(6\pi m/M)^{1/2}=0.85$ Å (giving a $d=2$ to 3 crossover at $\varepsilon\approx 3\times 10^{-3}$) was essentially as good as the 2D fit. Hence the simple 2D fluctuation conductivity fit appears to be the most reasonable for $\varepsilon > 3\times 10^{-3}$, in agreement with the results of Hagen *et al.*[14]

We would like to make three general remarks about the $\sigma_1(T)$ fits presented above. First, note that all the mean field T_c values are slightly above $T_{c\sigma}$, yet several kelvin below the T_c determined by susceptibility measurements, similar to dc fluctuation conductivity fits (see Table I). Note that when T_c is constrained to be either $T_{c\sigma}$, or the susceptibility T_c, very poor fits result. Next, all of our fits (2D, Klemm, 3D) show a sharp *slowing down* of the conductivity divergence below the fit range (see Fig. 2), in contrast with dc conductivity fits which show an *increase* in the rate of divergence in the analogous temperature range.[6] The slowing down occurs at about the same value of ε for all fits, $\varepsilon\sim(2\text{–}3)\times 10^{-3}$. However, this is not the slowing down predicted by TDGL theory (i.e., $\omega_0=1$), which is at $\varepsilon\sim 1\times 10^{-3}$ for YBCO at 9.6 GHz, suggesting that *something else limits the increase of the conductivity*. Note that the slowing down is robust against small changes in fit parameters, for instance it is quite insensitive to the choice of mean field conductivity, in agreement with Hagen *et al.*[14] Finally, it should be noted that our fits extend much closer to T_c than any of the dc fits in the literature, and do not show the unexplained sharp rise in conductivity as T approaches T_c from above.[6]

In examining $\sigma_1(T)$ peaks on a variety of crystals, we find empirically the rather surprising result that $\sigma_1(T_{c\sigma})=\sigma_2(T_{c\sigma})$ to good approximation in all crystals (as shown, for example, in Fig. 1).[4] The TDGL fluctuation theory[15] predicts that $\sigma_1^{\rm 3D,fluc}(T_c,\omega)=\sigma_2^{\rm 3D,fluc}(T_c,\omega)$, or equivalently the conductivity phase angle $\phi_\sigma\equiv\tan^{-1}(\sigma_2/\sigma_1)=\pi/4$ at T_c for 3D Gaussian fluctuations.[21] Theory also predicts that $\sigma_2^{\rm 2D,fluc}(T_c^-,\omega)$ diverges at T_c while $\sigma_1^{\rm 2D,fluc}(T_c,\omega)$ remains finite, or $\phi_\sigma=\pi/2$.[21] Hence our data is consistent with 3D, rather than 2D, fluctuations at $T_{c\sigma}$, implying a $d=2$ to 3 crossover for $\varepsilon\leqslant 3\times 10^{-3}$.

A quantitative analysis of Gaussian fluctuation conductivity shows that the extrapolated value at T_c for $\sigma_1^{\rm 2D,fluc}(T_c,\omega)=[e^2/(\hbar t)](k_BT_c/\hbar\omega)\approx 2.5\times 10^7\ \Omega^{-1}\,{\rm m}^{-1}$, is substantially greater than the measured $\sigma_1(T_{c\sigma},\omega)\sim 1.0\times 10^7\ \Omega^{-1}\,{\rm m}^{-1}$ (Fig. 1), while the value for $\sigma_1^{\rm 3D,fluc}(T_c,\omega)=[e^2/(12\hbar\xi_0)](k_BT_c/2\pi\hbar\omega)^{1/2}\sim 2\times 10^6\ \Omega^{-1}\,{\rm m}^{-1}$ is substantially less than $\sigma_1(T_{c\sigma},\omega)$, indicating that pure 2D or 3D Gaussian fluctuations do not dominate the measured conductivity for temperatures arbitrarily close to T_c. There must be another mechanism coming into play for $\varepsilon < 3\times 10^{-3}$ which influences $\sigma_1(T,\omega)$.

We see two possible explanations for the behavior of the conductivity near $T_{c\sigma}$. First, inhomogeneities in the transition temperature of the crystal may be responsible for limiting the increase in $\sigma_1(T)$.[16] A very simple effective medium model,[22] based on a Gaussian distribution of T_c's with variance $\sigma_{T_c}^2=0.24$ K^2, gives a surprisingly good description of the $\sigma_1(T)$ peak (this model is discussed in detail below). One finds that the peak height $[\sigma_1(T_{c\sigma})\sim 10^7\ \Omega^{-1}\,{\rm m}^{-1}]$, the peak width, and the fact that $\sigma_1(T_{c\sigma})\sim\sigma_2(T_{c\sigma})$, are all reproduced by the simple model. However, this model does not explain the detailed temperature dependence of the data for $\varepsilon > 3\times 10^{-3}$.

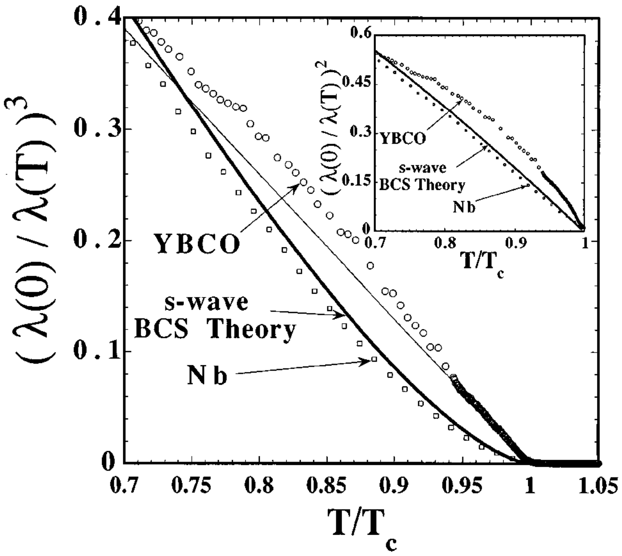

FIG. 3. $[\lambda(0)/\lambda(T)]^3$ vs T/T_c for YBCO (T_c=90.20 K) and Nb (T_c=9.20 K) single crystals, and s-wave BCS theory. The straight line is a guide to the eye. Inset shows $\lambda^2(0)/\lambda^2(T)$ vs T/T_c for YBCO (T_c=90.50 K) and Nb (T_c=9.20 K) single crystals, as well as s-wave BCS theory.

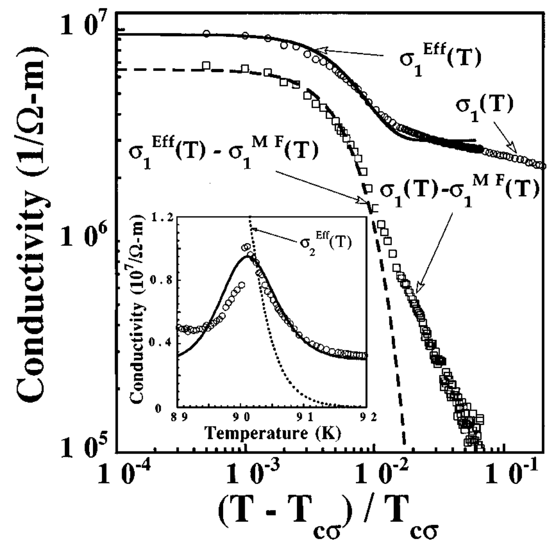

FIG. 4. Conductivity data $\sigma_1(T)$ (circles), calculated effective medium $\sigma_1^{\text{eff}}(T)$ (solid line), and the same two quantities with 2D mean field conductivity subtracted away (squares and dashed line, respectively). The inset shows the total conductivities on a linear scale near T_c, and also shows $\sigma_2^{\text{eff}}(T)$ from the effective medium model (dotted line).

A second possibility is critical fluctuations, suggested by examining the penetration depth $\lambda(T)$ below T_c, as shown in Fig. 3. Mean field theory predicts that the magnetic penetration depth in a superconductor diverges as $\lambda(T)/\lambda(0) \sim (1-T/T_c)^{-\beta}$ with β=1/2, as T_c is approached from below.[23] Hence a plot of $[\lambda(0)/\lambda(T)]^2$ vs T should be a straight line intersecting zero at the mean field transition temperature, T_c. The inset of Fig. 3 shows such a plot for a Nb single crystal, verifying that linear behavior is seen between 6.5 K and T_c ($\approx$9.2 K), consistent with BCS theory. When data for the ab-plane screening currents in YBCO is plotted, the data is clearly not linear from 65 K to T_c, suggesting non-mean-field behavior.

To identify 3D XY fluctuations, one can plot $[\lambda(0)/\lambda(T)]^{1/\beta}$, with β=0.33,[23] vs temperature (shown in Fig. 3). The YBCO data is now clearly linear from 85 K to T_c, a region of reduced temperature in which the Nb data and BCS theory are clearly not linear.[24] This 3D XY critical regime is at least 5 K wide, not quite as broad as that of Kamal's YBCO crystals,[3] but surprisingly wider than that estimated by Lobb ($\sim$1 K) on the basis of the Ginzburg criterion.[23,25] The same critical behavior of the penetration depth has been observed in thin films of $La_{2-x}Sr_xCuO_{4-\delta}$,[26] but not in thin films of YBCO.[27] Nevertheless, this asymmetry of the fluctuations observed here, primarily 2D and Gaussian above T_c vs 3D and critical below, is in qualitative agreement with Monte Carlo calculations in the anisotropic 3D XY model.[28]

These results below T_c suggest that we look for similar behavior in $\sigma_1(T)$ above T_c. We can estimate the width of the critical region as the range between $T_{c\sigma}$ and the point where 2D Gaussian fluctuations no longer describe the data, a width of approximately 0.6 K. Lobb has pointed out that the conductivity in the 3D XY model is expected to enter two critical regimes as $\varepsilon \to 0$, one characterized by $\sigma \sim \varepsilon^{-\nu}$, ν=2/3, and the second closer to T_c.[23] The latter critical regime is dominated by the divergence of the fluctuation relaxation time scale $\tau \sim \xi^z$, where $\xi \sim \varepsilon^{-\nu}$ is the correlation length, z and ν are the dynamical scaling and correlation length exponents, respectively, and $\sigma \sim \varepsilon^{-\nu(z+2-d)}$.[29,30]

Note that above T_c for the 2D and unconstrained Klemm fits, the data points in Fig. 2 for $\varepsilon < 3\times10^{-3}$ fall on a line segment of slope $-1/3$ to good approximation, suggestive of critical fluctuations in the conductivity, $\sigma \sim \varepsilon^{-1/3}$. However, as we saw from examining the penetration depth data below T_c, critical fluctuations have a T_c corresponding to the point where $1/\lambda^3(T)$ vanishes (at T=90.20 K$\cong T_{c\sigma}$). A plot of $\sigma_1(T)$, and $\sigma_1(T)-\sigma_1^{\text{MF}}(T)$, where the mean field conductivity was that giving the best 2D fit, versus $(T-T_{c\sigma})/T_{c\sigma}$ is shown in Fig. 4. From this figure it is clear that there is no region near $T_{c\sigma}$ in which the conductivity has a simple power law dependence on $(T-T_{c\sigma})/T_{c\sigma}$. Instead, we find that the effective medium model mentioned above[16,22] $[\sigma_1^{\text{eff}}(T)$ shown as solid lines in Fig. 4, and $\sigma_2^{\text{eff}}(T)$ shown as a dotted line in the inset$]$ gives a good quantitative description of the $\sigma_1(T)$ and $\sigma_2(T)$ data for $(T-T_{c\sigma})/T_{c\sigma} < 10^{-2}$. The model reproduces the slowing down of the conductivity divergence using a Gaussian spread of T_c of standard devia-

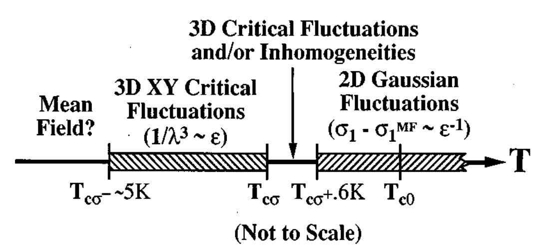

FIG. 5. Schematic summary of conclusions regarding the nature of superconducting fluctuations in the vicinity of T_c of a YBCO single crystal (not to scale). Here $T_{c\sigma}$=90.11 K and T_{c0} represents the dc zero resistance temperature ($T_{c0} \cong$92 K).

tion 0.49 K, with a central T_c of 90.9 K, $\lambda(0)=1400$ Å, and a two-fluid conductivity below T_c (Ref. 11) with a normal state conductivity of 3×10^6 $(\Omega\ \mathrm{m})^{-1}$. The same conclusions are obtained when T_c is chosen as the point where $1/\lambda^3(T)$ goes to zero (T_c=90.20 K). Hence we conclude that the response within 0.6 K above $T_{c\sigma}$ cannot be attributed entirely to critical fluctuations in $\sigma_1(T)$.

Our conclusions regarding the nature of superconducting fluctuations in this YBCO crystal are summarized in Fig. 5. Broadly speaking, we find that fluctuation effects in YBCO crystals are asymmetric about T_c. The fluctuations are 3D and *critical* below T_c, with evidence of 3D *XY* scaling within 5 K of T_c. It is not clear from our data on the penetration depth temperature dependence that mean field behavior is ever fully recovered at lower temperatures. Whereas above T_c we find the data shows two-dimensional *Gaussian* finite frequency conductivity fluctuations for $\varepsilon>3\times10^{-3}$, and slowing down behavior most likely due to inhomogeneities closer to T_c. The width of the critical region above T_c, if it exists, is at most about 0.6 K wide.

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[25] The $\lambda_{\mathrm{eff}}(T)$ data and $\lambda_c(T)$ determined in Ref. 4 are also consistent with 3D *XY* behavior near T_c. Also note that finite size effects are not important here since $\xi(T)\approx10$ Å$/\varepsilon^{\nu}$, with $\nu=1/2$ or 2/3, does not approach the sample size until $\varepsilon\sim10^{-9}$. A discussion of finite size effects in penetration depth measurements and how they can affect the critical behavior is given in Ref. 27.
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