Cuprate superconductors show much stronger thermodynamic fluctuations than classical ones because of their higher transition temperatures ($T_c$), shorter Ginzburg-Landau (GL) coherence lengths, and quasi-two-dimensional layered structures with weakly interacting CuO$_2$ planes.$^{1,2}$ Observations of diamagnetism$^{3}$ and large Nernst coefficients over a broad temperature ($T$) range well above $T_c$ for several types of cuprate$^{4,5}$ are intriguing. They are often cited as evidence of indirect coupling in some way to the pairing mechanism.$^6$ Nevertheless, the fluctuation cutoff could be of general interest because superconducting fluctuations could be altered, including extremely sharp x-ray peaks,$^{13}$ and substantial mean free paths from quantum oscillation measurements.$^{14}$ The OD89 crystal is from another preparation batch which had narrow superconducting transitions and a maximum $T_c$ of 93.8 K.$^{15}$ We analyze the results using GF theory which, unlike some other approaches, predicts the magnitude of the observed effects as well as their $T$ dependence. We show that it gives excellent single-parameter fits to the magnetic susceptibility and other physical properties.$^1$

One difficulty in this area is separating the fluctuation (FL) contribution to a given property from the normal state (N) background. Recently this has been dealt with for the in-plane electrical conductivity $\sigma_{ab}(T)$ of YBa$_2$Cu$_3$O$_{6+x}$ crystals by applying very high magnetic fields ($B$).$^9$ When analyzed using GF theory, $\sigma^{\text{FL}}_{ab}(T)$ was found to cut off even more rapidly above $T \geq 1.1T_c$ than previously thought.$^{10,11}$ It was also strongly reduced at high $B$ and the fields needed to suppress $\sigma^{\text{FL}}_{ab}(T)$ extrapolated to zero between 120 and 140 K depending on $x$, which tends to support a vortex or Kosterlitz-Thouless scenario. Therefore questions such as the applicability of GF theory versus a phase fluctuation or mobile vortex scenario and the extent to which $T_c$ is suppressed below $T_c^{\text{MF}}$ by strong critical fluctuations are still being discussed. They are of general interest because superconducting fluctuations could limit the maximum $T_c$ that can be obtained in a given class of material,$^7$ and, moreover,$^9$ the fluctuation cutoff could be linked in some way to the pairing mechanism.

Here we report torque magnetometry data$^{12}$ for $T_c$ to 300 K for tiny YBa$_2$Cu$_3$O$_{6+x}$ (YBCO) single crystals from overdoped (OD) to heavily underdoped (UD). These were grown in nonreactive BaZrO$_3$ crucibles from high-purity (5N) starting materials. Evidence for the quality of the UD crystals includes extremely sharp x-ray peaks,$^{13}$ and substantial mean free paths from quantum oscillation measurements.$^{14}$ The OD89 crystal is from another preparation batch which had narrow superconducting transitions and a maximum $T_c$ of 93.8 K.$^{15}$ We analyze the results using GF theory which, unlike some other approaches, predicts the magnitude of the observed effects as well as their $T$ dependence. We show that it gives excellent single-parameter fits to the magnetic susceptibility and other physical properties.$^1$

Although measurements of the London penetration depth$^{16}$ below $T_c$ and thermal expansion$^{17}$ above and below $T_c$ for optimally doped (OP) YBCO crystals give evidence for critical fluctuations described by the three-dimensional (3D) XY model, up to $\pm 10$ K from $T_c$, we argue later that these do not alter our overall picture.

A crystal with magnetization $M$ in an applied magnetic field $B$ attached to a piezoresistive cantilever causes a change in electrical resistance proportional to the torque density $\tau \equiv M \times B$. If $B$ is parallel to the $c$ axis of a cuprate crystal, then in the low-field limit the contribution to $M$ in the $c$-axis direction from Gaussian fluctuations ($M_c^{\text{FL}}$) is given by

$$M_c^{\text{FL}}(T) = -\frac{\pi k_B T B}{3\Phi_0} \frac{\xi_0^2(T)}{s \sqrt{1 + (2\xi_0^2(T)/\gamma s)^2}}. \tag{1}$$

Here $\gamma \equiv \xi_0(T)/\xi_c(T)$ is the anisotropy, defined as the ratio of the $T$-dependent coherence lengths $\parallel$ and $\perp$ to the planes, i.e., $\xi_{ab,c}(T) = \xi_{ab,c}(0)e^{\epsilon/\epsilon}$ with $\epsilon = (T/T_c^{\text{MF}})^2$.$^{2,9}$

The distance between the CuO$_2$ bilayers is taken as $s = 1.17 \text{ nm}$, and $\Phi_0$ and $k_B$ are the pair flux quantum and Boltzmann’s constant, respectively. For $B \perp c$ the fluctuation magnetization is negligibly small.

As the angle $\theta$ between the applied field and CuO$_2$ planes is altered, $\tau(\theta)$ will vary as $\tau(\theta) = \frac{1}{2} \chi_D \left( T \right) B^2 \sin 2\theta$, as long as $M \ll B$. Thus, fits to $\tau(\theta) \propto B^2 \sin 2\theta$ give $\chi_D(T) \equiv \chi_c(T)$...
The solid lines for OD89 and UD57 are fits up to 300 K studies of the conductivity χ_N described below, plus the normal state background anisotropy nonlinearity in paramagnetism.18 For UD crystals the χ_{ab} and subtracting the gravitational term (Ref.12). The solid lines show single-parameter fits to the formula for 2D GF derived from Eq. (2) plus χ_D(T) shown in Fig. 2(a). Note the sin 2θ behavior at higher T.

χ_{ab}(T), which is the susceptibility anisotropy. Figure 1 shows torque data for UD57 up to 15 K above the low-field Tc of 57 K. Much of our data, including the two curves for UD57 in Fig. 1 at higher T, follow a sin 2θ dependence very closely, however, there are striking deviations at lower T arising from nonlinearity in M(B) that we discuss later.

Figure 2(a) shows χ_D(T) obtained from sin 2θ fits for three doping levels at high enough T so that M remains ∝ B. The solid lines for OD89 and UD57 are fits up to 300 K that include χ_{FL}(T) from Eq. (1), with the strong cutoff described below, plus the normal state background anisotropy χ_N(T) which arises from the g-factor anisotropy of the Pauli paramagnetism.18 For UD crystals the T dependence of χ_N(T) is caused by the pseudogap (see Ref. 19), plus a smaller contribution from the electron pocket19 observed in high-field quantum oscillation studies.20 We used the same pseudogap energies (k_B T*) and other parameters defining χ_N(T) as in our recent work on larger single crystals,18 e.g., T* = 435 K for UD57. OD89 has no pseudogap and presumably no pockets, so we represent the weak variation of χ_N(T) with T by the second order polynomial shown in Fig. 2(a).

Figures 2(b)–2(d) show plots of 1/|χ_{c}(T)| vs T where χ_{c}(T) ≡ χ_c(T) − χ_N(T). The short-dashed lines for UD22 and UD57 in Figs. 2(b) and 2(c) show the contribution from Eq. (1) in the 2D limit (γ → ∞) with the two adjustable parameters T_c^{MF} and ξ_{ab}(0) given in Table I. The solid lines show the effect of the same type of cutoff used in previous studies of the the conductivity σ_{FL}(T, B), as summarized in Ref. 21. For OD89 we use the full 2D-3D form of Eq. (1) with ξ_{ab}(0) = 1.06 nm and γ = 5.22 shown by the short-dashed line, with the solid line again including the cutoff.21 The high quality of these fits could be somewhat fortuitous in view of our neglect of any charge density wave (CDW).19 but other subtraction procedures give similar values of 1/|χ_{FL}(T)|. Heat capacity studies give a very similar value ξ_{ab}(0) = 1.12 nm for OD88 YBCO (Ref. 24) while our values for UD57 and UD22 agree with previous work15,25 for the same T_c values. For UD57, setting γ = 45.26 rather than the 2D limit of Eq. (1) (γ → ∞), has no significant effect.

As the critical region is approached from above T_c the exponent of ξ_{ab}(T) is expected to change from the MF value of −1/2 to the 3D XY value of −2/3.1 It is very likely that this will also apply to strongly 2D materials, including UD57, since heat capacity data above and below T_c (Ref. 27) do show the ln |ε| terms associated with the 3D XY model. We have
addressed this by repeating our GF fits in Figs. 2(b) and 2(c) with $\epsilon \geq 0.20$ (UD22) or 0.15 (UD57) without altering the cutoff.\(^{31}\) The only significant change is that $\xi_{ab}(0)$ becomes 15% larger for UD57. For OD98, fits with $T_{\text{MF}}^{\text{OD}} = 90$ K and $\epsilon \geq 0.05$ do not alter $\xi_{ab}(0)$ within the quoted error. This is expected since the width of the critical region for OD98 is much smaller than for OP YBCO (Refs. 16, 17) because of the extra 3D coupling from the highly conducting CuO chains.\(^{24}\)

Figure 3 shows plots of $\tau / B \cos \theta$ vs $B \sin \theta$ at fixed $T$ for UD57. We use this representation of the data and mks units, $\lambda / T_{c}$ and $M_0$, for comparison with Ref. 3. If $\chi_0^{\text{FL}}(T)$ is subtracted, which has not been done for Fig. 3, then since $M_{\text{FL}}^{(0)}$ is small, this would be the same as plotting $M_{\text{FL}}^{(0)}$ vs $B || c$. Near $T_c$ there is clear nonlinearity which is remarkably consistent with GF in the 2D limit, for which the free energy density at all $B$ is\(^{2}\)

$$F = \frac{k_B T}{2\pi \xi_{ab}^2} \left( b \ln \left[ \left( \frac{1}{2} \right)^{\epsilon / 2b} \right] + \frac{\epsilon}{2} \ln(b) \right) \left( 1 - \frac{\pi}{2b} \right)$$

using the standard $\Gamma$ function, with $b = B / \tilde{B}_c(0)$, where $\tilde{B}_c(0) = \Phi_0 / 2\pi \xi_{ab}(0)^2$, and as before, $\epsilon = \ln[T / T_c^{\text{MF}}(B = 0)]$. The magnetization $M = -\partial F / \partial B$ obtained by numerical differentiation of Eq. (2) for three typical values of $\epsilon$ is shown in the inset to Fig. 2(a). $M$ scales with $b/\epsilon$ to within a few percent and for $0.1 < \epsilon < 1$ can be adequately represented by the simple formula $-b k_B T / (\Phi_0 (3b + 6c))$, which has a single unknown parameter $\xi_{ab}(0)^2 / \epsilon$. We note that GF formulas will be approximately valid in the crossover region to 3D XY behavior,\(^{1}\) because to first order the main effect is the change in the exponent of $\xi_{ab}(T)$.

**TABLE I. Summary of results.**

| Sample | $T_c$<sup>a</sup> (K) | $T_c^{\text{MF}}$<sup>a</sup> (K) | $\xi_{ab}(0)$ (nm) | $0.59 \tilde{B}_c(0)$<sup>b</sup> (T) | $\Delta(0)$<sup>c</sup> (K) |
|--------|----------------|----------------|-------------------|----------------|----------------|
| OD98   | 89.4           | 89.7           | 1.06 ± 0.1        | 173            | 448            |
| UD57   | 56.5           | 59             | 2.02 ± 0.1        | 48             | 234            |
| UD22   | 21.6           | 24             | 4.5 ± 0.5         | 10             | 105            |

\(^a\) $T_c$ defined by sharp onsets of superconducting quantum interference device (SQUID) signal at 10 G and torque data at ±50 G. \(^b\) 2D clean limit formula (Ref. 2) for $B_c(0)$. \(^c\) From the BCS relation $\xi_{ab}(0) = \frac{\hbar^2}{\pi m_e T_c}$, which may not hold exactly for $d$-wave pairing, with $\nu_f = 2 \times 10^5$ cm/s. \(^3\)

Figures 1 and 3 show that this formula fits our data for UD57 very well and importantly, as shown by the red triangles in Fig. 2(c), the corresponding values of $1 / \chi_0^{\text{FL}}(T)$ obtained via Eq. (1) agree well with points from sin $2\theta$ fits at lower $B$ or higher $T_c$. For OD98 strong deviations from sin $2\theta$ behavior only occur within $\sim 1$ K of $T_c$, and these\(^{25}\) are not properly described by GF theory. For UD22 there were small jumps in $\tau(\theta)$ at $\theta = 0$ between 35 and 26 K of size $M_c = 0.01 - 0.03k_B T / (3\Phi_0 s)$ that were fitted by including an extra contribution from Eq. (2) in the $\epsilon \ll b$ limit. This is ascribed to small regions, 1%–3% of the total volume, with higher $T_c$ (Ref. 29) that are not detected in low-field measurements of $T_c$ because they are much smaller than the London penetration depth. Figure 2(b) shows that the values of $\xi_{ab}(0)^2 / \epsilon$ or equivalently $1 / \chi_0^{\text{FL}}(T)$ obtained from full GF fits to $\tau(\theta)$ data at 2, 5, and 10 T agree well, which supports this conclusion.

The good description of our data by this GF analysis suggests that the high critical fields proposed in Refs. 3–5 for $0.01 < \epsilon < 0.2$ are not associated with vortex-like excitations. In the present picture 2D GF give $M_{\text{FL}}^{(0)} \approx -0.33k_B T / \Phi_0 s = -0.112$ emu/cm$^2$ or $-112$ A/m at 60 K for $B \gg \Phi_0 / (2\pi \xi_{ab}(0)^2)$. We expect this to be suppressed for $B \gg B_c(0)$ where the magnetic length becomes smaller than $\xi_{ab}(0)$ and the slow spatial variation approximation of GL theory breaks down. However, it may also fall when $\epsilon \leq 0.1$ because of the GF cutoff discussed below. So in the first approximation the high fields are $\sim B_c(0)$. Precise analysis of these effects at very high fields might need to allow for small changes in $\chi_0^{\text{FL}}(T)$ with $B$ that depend on the ratio of the Zeeman energy to the pseudogap. We note that the present results are consistent with a recent study of $B_c(2)$ for YBCO (Ref. 30) and that recent torque magnetometry data\(^{31}\) for HgBa$_2$CuO$_{4+\delta}$ and other single-layer cuprates show similar exponential attenuation factors to those for YBCO.\(^{2,31}\)

An intriguing question about the present results and those of Ref. 9 is the origin of the strong cutoff in the GF above $\sim 1.17T_c$. If the weakly $T$-dependent $\chi_0^{\text{FL}}(T)$ behavior for OD98 shown in Fig. 2(a) is correct, then our $\chi_0^{\text{FL}}(T)$ data and $\sigma_{ab}^{\text{FL}}(T)$ (Ref. 9) both decay as $\exp[-(T - 1.08T_c)/T_0] > 0$ above $T_c \sim 0.8 T_c$ with $T_0 \sim 9$ K. If instead $\chi_0^{\text{FL}}(T)$ were constant below 200 K, then our $\chi_0^{\text{FL}}(T)$ data would give $T_0 \sim 25$ K, a slower decay than Ref. 9. In either case the presence of this cutoff for OD YBCO rules out explanations connected with the mean distance between carriers. This is much less than $\xi_{ab}(0)$ for hole concentrations of $\approx 1.2$ per CuO$_2$ unit, the value found directly from quantum oscillation studies of OD Tl$_2$Ba$_2$CuO$_{6+\delta}$ crystals.\(^{32}\)

Assuming there are no unsuspected effects caused by $d$-wave pairing, one hypothesis is that the GF and possibly $T_c$ itself are suppressed by inelastic scattering processes. In a quasi-2D Fermi liquid the inelastic mean free path $l_m$ can be found from the $T$ dependence of the electrical resistivity and the circumference of the Fermi surface. For OD YBCO the measured $a$-axis resistivity\(^{25}\) gives $l_m = 2.5(100/T)$ nm, but values for UD samples are less certain because of the pseudogap. The BCS relation $\xi_{ab}(0) = \hbar v_F / \pi \Delta(0)$, where $\Delta(0)$ is the superconducting energy gap at $T = 0$, implies that, irrespective of the value of the Fermi velocity $v_F$, the usual pair-breaking condition for significant inelastic scattering,
$\hbar/\tau_0 \geq \Delta(0)$, is equivalent to $\tau_0 \lesssim \pi \xi_{ab}(0)$. Taking $\xi_{ab}(0)$ from Table I and the above value of $\tau_0$, shows that this is satisfied at 100 K for OD YBCO. So some suppression of GF and indeed $T_c$ by inelastic scattering is entirely plausible. If $T_c$ is suppressed, then $\Delta(T)$ will fall more quickly than BCS theory as $T_c$ is approached from below, which would affect the analysis of Ref. 7.

Another possibility, which might account for the observations is that the pairing strength itself falls sharply outside the GL region, for example, when the in-plane coherence length becomes comparable to, or less than, the correlation length of spin fluctuations. From Figs. 2(b)—2(d) we can read off the values of $\chi_{l}^{c}(0)$ where the solid and dashed lines differ by (say) a factor of 2. At these points $\xi_{ab}(T) \equiv \xi_{ab}(0)/\ln(T/T_{c}^{MF}) = 15.6$, 9.5, and 7.9 nm for UD22, UD57, and OD89, respectively. Neutron scattering studies typically give a full width at half maximum of 0.17 $\Delta(0)$ for the scattering intensity from spin fluctuations. Although this does vary with composition and scattering energy, it corresponds to a correlation length of just over six lattice constants. Allowing for $\xi_{ab}(0)$ but much smaller than the $\xi_{ab}(T)$ values for which $\chi_{l}^{c}$ is reduced by a factor of 2. It remains to be seen whether theory could account for this.

In these two pictures the effective $T_c$, describing the strength of the GF would fall for $T > 1.1T_c$ either because of inelastic scattering or because of a weakening of the pairing interaction. If it could be shown theoretically that $B_{c2}(0)$ falls in a similar way, this would account naturally for the fact that the magnetic fields needed to destroy the GF fall to zero in the temperature range 120–140 K, where the fluctuations become very small. In summary, Gaussian superconducting fluctuations, plus a strong cutoff that seems to be linked to a reduction in the effective value of $T_c$, provide a good description of the diamagnetism of our superconducting cuprate crystals above $T_c$.

We are grateful to D. A. Bonn, A. Carrington, W. N. Hardy, G. G. Lonzarich, J. W. Loram, and L. Taillefer for several helpful comments. This work was supported by EPSRC (U.K.), Grant No. EP/C511778/1, and the Croatian Research Council, MZOS Project No. 119-1191458-1008.

---

1. I. Kokanović, J. R. Cooper, and K. Iida, Europhys. Lett. 88, 060505(R) (2013).
2. M. R. Cimberle, C. Ferdeghini, E. Giannini, D. Marre, M. Putti, A. Siri, F. Federici, and A. Varlamov, Phys. Rev. B 55, R14745 (1997).
3. C. Carballeira, S. R. Curras, J. Vina, J. A. Veira, M. V. Ramallo, and F. Vidal, Phys. Rev. B 63, 144515 (2001).
4. The crystal is glued to the end of a commercial piezolever with its CuO$_2$ planes parallel to the flat surface of the lever. A dummy lever compensates background magnetoresistance signals, using a three-lead Wheatstone bridge circuit driven by a floating 77 Hz current source. The chip is mounted on a single-axis rotation stage inside a He cryomagnetic system providing stable temperatures from 1.4 K up to 400 K and fields up to 15 T. The bridge signal arising from the gravitational torque on the crystal when the sample stage is rotated in zero magnetic field gives the $T$-dependent sensitivity of the piezolever. Because the masses of the glue and the lever are much less than that of the crystal, the calibration constant relating the out-of-balance bridge signal to the angular-dependent torque density $\tau(\theta)$ in J/m$^3$ or $\tau(\theta)$ (Ref. 37) only depends on the distance between the center of mass of the crystal and the base of the lever at the silicon chip, measured to $\pm 5\%$.
5. R. Liang, D. A. Bonn, and W. N. Hardy, Physica C 336, 57 (2000).
6. A. Audouard, C. Jaudet, D. Vignolles, R. Liang, D. A. Bonn, W. N. Hardy, L. Taillefer, and C. Proust, Phys. Rev. Lett. 103, 157003 (2009).
7. N. M. Kirby, A. Trang, A. van Riessen, C. E. Buckley, V. W. Wittorff, J. R. Cooper, and C. Panagopoulos, Supercond. Sci. Technol. 18, 648 (2005).
8. S. Kamal, D. A. Bonn, N. Goldenfeld, P. J. Hirschfeld, R. Liang and W. N. Hardy, Phys. Rev. Lett. 73, 1845 (1994).
9. V. Pasler, P. Schweiss, C. Meingast, B. Obst, H. Wühl, A. I. Rykov, and S. Tajima, Phys. Rev. Lett. 81, 1094 (1998).
10. I. Kokanović, J. R. Cooper, and K. Ida, Europhys. Lett. 98, 57011 (2012).
11. A recent hard x-ray study of UD67 YBCO gives evidence (Ref. 38) for CDW order developing gradually below 150 K that is almost
T. Pereg-Barnea, P. J. Turner, R. Harris, G. K. Mullins, J. S. Y. Ando and K. Segawa, Phys. Rev. Lett.

J. W. Loram, J. R. Cooper, J. M. Wheatley, K. A. Mirza, and R. S. Liu, Philos. Mag. B 65, 1405 (1992).

Y. Ando and K. Segawa, Phys. Rev. Lett. 88, 167005 (2002).

T. Pereg-Barnea, P. J. Turner, R. Harris, G. K. Mullins, J. S. Bobowski, M. Raudsepp, R. Liang, D. A. Bonn, and W. N. Hardy, Phys. Rev. B 69, 184513 (2004).

J. W. Loram, J. L. Tallon, and W. Y. Liang, Phys. Rev. B 69, 060502(R) (2004).

Although the 2D-3D form of Eq. (2) (Ref. 2) with \( r = 0.13 \) describes the non-sin\( 2\theta \) shape of \( \tau(\theta) \), the calculated values of \( M/\tau \) are a factor of 3 too small, and \( \epsilon \) is far too small compared with the low-field transition width arising from inhomogeneity or strain. This non-GF behavior is ascribed to \( T_c \) being too close to \( T_c \).

A. Lascialfari, A. Rigamonti, L. Romano, P. Tedesco, A. Varlamov, and D. Embriaco, Phys. Rev. B 65, 144523 (2002).

J. Chang, N. Doiron-Leyraud, O. Cyr-Choinière, G. Grissonnanche, F. Laliberté, E. Hassinger, J.-Ph. Reid, R. Daou, S. Pyon, T. Takayama, H. Takagi, and L. Taillefer, Nat. Phys. 8, 751 (2012).

G. Yu, D.-D. Xia, N. Barisic, R.-H. He, N. Kaneko, T. Sasagawa, Y. Li, X. Zhao, A. Shekhter, and M. Greven, arXiv:1210.6942.

P. M. C. Rourke, A. F. Bangura, T. M. Benseman, M. Matusiak, J. R. Cooper, A. Carrington, and N. E. Hussey, New J. Phys. 12, 105009 (2010).

S. M. Hayden, H. A. Mook, P. Dai, T. G. Perring, and F. Dogan, Nature (London) 429, 531 (2004).

C. Stock, W. J. L. Buyers, R. Liang, D. Peets, Z. Tun, D. Bonn, W. N. Hardy, and R. J. Birgeneau, Phys. Rev. B 69, 014502 (2004).

C. Kittel, Introduction to Solid State Physics, 8th ed. (Wiley, New York, 2005), Chap. 2.

L. P. Gorkov, Sov. Phys. JETP 9, 1364 (1959).

Units: 1 J/m\(^3\) = 10 ergs/cm\(^3\) and using CGS units for \( \tau(\theta) \) in gauss gives \( \chi_D \) in emu/cm\(^3\). Complete flux exclusion corresponds to \( \chi = -1/4\pi \) emu/cm\(^3\), or \( \chi = -1 \) in mks units. For YBCO, \( \chi_D \) in emu/cm\(^3\) is multiplied by the volume per mole, 666/6.38 cm\(^3\), to convert to emu/mol.

E. Blackburn, J. Chang, M. Hucker, A. T. Holmes, N. B. Christensen, R. Liang, D. A. Bonn, W. N. Hardy, M. v. Zimmermann, E. M. Forgan, and S. M. Hayden, Nat. Phys. 8, 871 (2012).

A. Pourret, H. Aubin, J. Lesueur, C. A. Marrache-Kikuchi, L. Berge, L. Dumoulin, and K. Behnia, Phys. Rev. B 76, 214504 (2007).