Effects of pressure on the fluctuation conductivity of $YBa_2Cu_3O_7$

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The effects of hydrostatic pressure up to 1.11 GPa on the in-plane fluctuation conductivity of $YBa_2Cu_3O_{7-d}$ are investigated. The experiments are focused on the asymptotic region closely above T_c where a three-dimensional Gaussian and genuine critical regimes are identified. From the analysis of the Gaussian critical amplitude one deduces that the off-plane coherence length $\xi_c(0)$ does not change significantly with pressure in the studied range. At low applied pressures the asymptotic critical exponent indicates the occurrence of a scaling beyond three-dimensional *XY*. However, at the highest studied pressure, this exponent assumes a value consistent with the predictions of the full-dynamic three-dimensional *XY* universality class. The width of the critical regime, as measured by the Ginzburg criterium, increases significantly with pressure. This result is related to a pressure-induced reduction of the in-plane coherence length $\xi_{ab}(0)$.

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Historically, high pressure studies have been extremely important to achieve a better understanding of the physical properties in every class of superconductors.[1] Particularly in the case of the high critical temperature cuprate superconductors (HTSC), a considerable effort has been devoted to high pressure investigations.[2] However, in spite of the fact that pressure allows a fine tuning of the critical temperature and produces sizable modifications of the electrical transport in the normal phase, only few reports studying the effects of pressure on the fluctuation electrical conductivity of the HTSC are available. Experimental studies were performed on ceramic $RBa_2Cu_3O_{7-d}$ $(R=Y,Gd,Er,Yb)$,[3] polycrystalline textured $Bi_2Sr_2CaCu_2O_{8+y}$,[4] and polycrystalline $HgBa_2Ca_2Cu_3O_8$.[5] These investigations are basically concerned with the pressure influence on the Gaussian fluctuation regimes in temperatures not too close to T_c.

In the present work we report on in-plane resistivity measurements under hydrostatic pressures up to $P=1.11$ GPa on a $YBa_2Cu_3O_{7-d}$ (YBCO) single crystal. We studied the thermal fluctuations' contribution to the conductivity and focused on the asymptotic regimes very close to the pairing transition. We were thus able to discern pressure effects on the regimes governed by genuine critical fluctuations.[6,7] When the temperature was increased enough above T_c, we could also observe a regime dominated by three-dimensional Gaussian (3D-*G*) fluctuations, which is robust against the variation of *P* in the studied range. The observation of critical and mean-field fluctuation regimes allowed us to determine the behavior of the Ginzburg number upon the pressure variation.

Our YBCO single crystal is strongly twinned and was grown with the self-flux method in a gold crucible, as described elsewhere.[8] The electrical resistivity was measured using a low-current and low frequency ac technique where a decade transformer is employed to generate a compensation signal, and a lock-in amplifier operates as a null detector. Silver epoxy contacts were glued to the extremities of the crystal in order to produce a uniform current distribution in the central region where voltage probes in the form of parallel stripes were placed. Contact resistances below 1 Ω were obtained. Temperatures were measured with a Pt sensor having an accuracy about 1 mK. The hydrostatic pressure was generated inside a Teflon cup housed in a copper–berillyum piston-cylinder cell, as described by Thompson.[9] A manganin gauge made of a 25 Ω wire was used to determine the applied pressures. Transformer oil was used as the transmitting medium and pressures were changed at room temperature in the order of increasing magnitude. For each applied pressure, experimental runs were carried at least twice, by cooling and heating the sample at rates never exceeding 3 K/h. A large number of closely spaced points were registered so that the temperature derivative of resistivity could be accurately calculated in the temperature range near T_c.

Measurements of the temperature dependence of the resistivity ρ_{ab} at constant *P* are shown in Fig. 1. In spite of the relatively large absolute values, probably due to scattering by gold impurities,[10] the resistivity in our crystal shows the expected behavior of well oxygenated samples. In temperatures above 140 K, ρ_{ab} varies linearly with *T* at rates $d\rho_{ab}/dT = 2.80$, 2.71, 2.51, and 2.45 $\mu\Omega\,\mathrm{cm\,K^{-1}}$ for the pressures $P = 0$, 0.45, 0.76, and 1.11 GPa, respectively. The relative change of ρ_{ab} as a function of pressure is practically temperature independent above 140 K and amounts to $d\ln\rho_{ab}/dP = -13(\pm 1)\%\ \mathrm{GPa}^{-1}$. This value is in agreement with previous determinations.[2] Figure 2 magnifies the resistive transition of our sample. Results are presented as ρ_{ab} vs

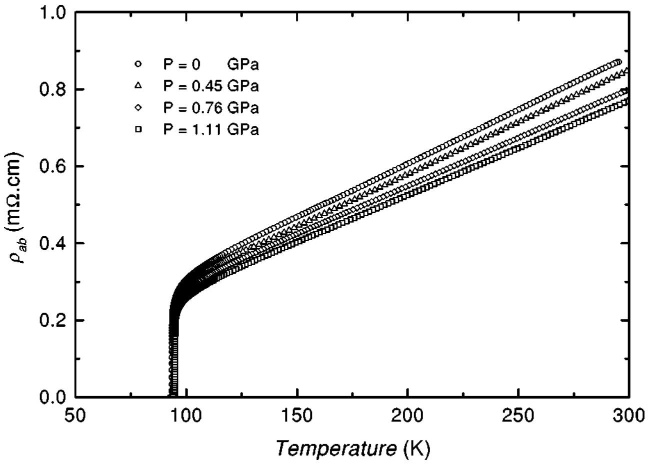

FIG. 1. In-plane resistivity of our YBCO crystal as a function of T in the quoted hydrostatic pressures.

T in panel (a) and $d\rho_{ab}/dT$ vs T in panel (b). Assuming that the pronounced maximum in $d\rho_{ab}/dT$ gives approximately the position of the critical temperature, we deduce that T_c increases with pressure at a rate $dT_c/dP \cong +1.3$ K GPa^{-1}, which is larger than the average but still within the range of observed values in well oxygenated YBCO.[2,11]

The fluctuation conductivity near T_c is obtained from the experimental data as

$$\Delta\sigma = \frac{1}{\rho_{ab}} - \frac{1}{\rho_R}, \tag{1}$$

where ρ_R is the regular resistivity obtained by extrapolating the linear behavior observed at high temperatures. In the analysis of the results, we adopt the simplest approach that describes the pressure-dependent fluctuation conductivity as a power law of the type

$$\Delta\sigma(T,P) = At^{-\lambda}, \tag{2}$$

where $t=[T-T_c(P)]/T_c(P)$ is the pressure-dependent reduced temperature, λ is the critical exponent and A is the critical amplitude. An efficient technique to study the asymptotic fluctuation regimes in the conductivity makes use of the numerically determined quantity[12]

$$\chi_\sigma = -\frac{d}{dT}\ln\Delta\sigma. \tag{3}$$

Thus, from Eq. (2), one obtains

$$\chi_\sigma^{-1} = \lambda^{-1}(T - T_c), \tag{4}$$

which allows the simultaneous determination of λ and T_c from simple identification of linear temperature behavior in plots of χ_σ^{-1} vs T. Having defined the temperature region where Eq. (4) is obeyed, the amplitude A may be calculated from Eq. (2) by substituting in it the previously determined values for λ and T_c.

In Fig. 3 we show representative results for $\chi_\sigma^{-1}(T)$ under the studied pressures. In a short temperature interval closely above $T_c(P)$, two linear regions are clearly discerned and fitted to straight lines. When $T_c(P)$ is approached from above, we first notice a linear region corresponding to a power law regime in $\Delta\sigma$ whose exponent is $\lambda_G \cong 0.5$. This regime is observed for all of the applied pressures. When the temperature is further decreased towards $T_c(P)$, a marked crossover to a fluctuation regime described by the small exponent labeled as λ_{cr} is observed in χ_σ^{-1}. As listed in Table I, this exponent has a value $\lambda_{cr}=0.18\pm0.02$ in pressures up to 0.76 GPa, and changes to $\lambda_{cr}=0.32\pm0.02$ in $P=1.11$ GPa.

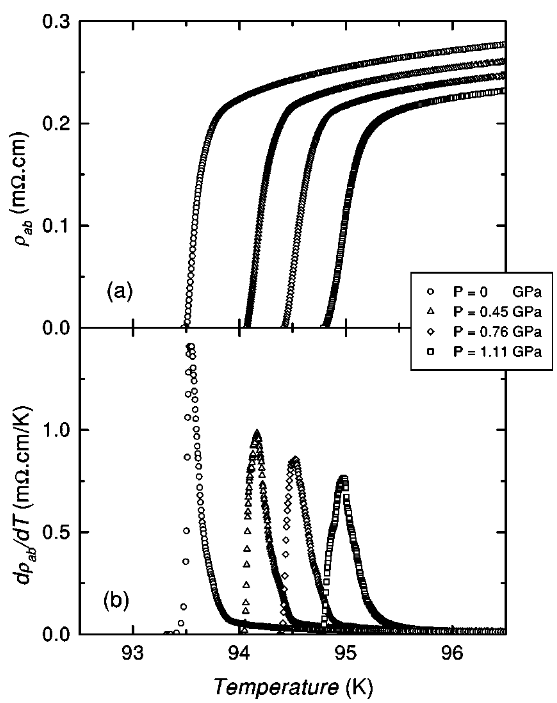

FIG. 2. Resistive transition of YBCO under the quoted pressures plotted as (a) resistivity vs T and (b) temperature derivative of the resistivity vs T.

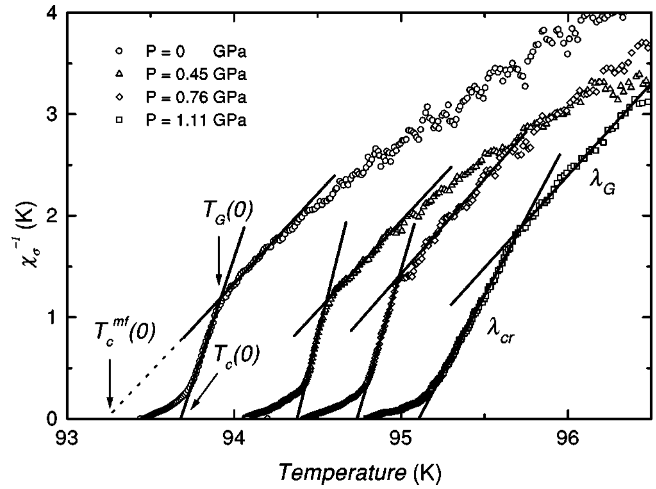

FIG. 3. Inverse logarithmic derivative of the conductivity χ_σ^{-1} as a function of T near the superconducting transition for the pressures $P=0$, 0.45, 0.76, and 1.11 GPa. Curves are displaced to the right in the order of increasing pressures. The straight lines correspond to fits to Eq. (4) and are labeled by the exponents λ_G and λ_{cr} listed in Table I. The temperature T_G identifies the Ginzburg temperature.

TABLE I. Values obtained in the studied pressures for the Gaussian (λ_G) and critical (λ_{cr}) exponents for the in-plane fluctuation conductivity in YBCO. Also listed are the off-plane coherence length $\xi_c(0)$ deduced from the Gaussian critical amplitudes and the Ginzburg numbers.

P(GPa)	λ_G	$\xi_c(0)$(nm)	λ_{cr}	Gi
0	0.50(±0.08)	0.12	0.19(±0.02)	0.006
0.45	0.56(±0.05)	0.14	0.16(±0.02)	0.007
0.76	0.53(±0.03)	0.13	0.19(±0.03)	0.008
1.11	0.55(±0.03)	0.15	0.32(±0.02)	0.011

The critical exponent for fluctuation conductivity may be written as[7]

$$\lambda = \upsilon(2 - d + z - \eta), \tag{5}$$

where υ is the critical exponent for the coherence length, d is the dimensionality of the fluctuation spectrum, z is the dynamical exponent, and η is the small exponent of the order-parameter correlation function. The Ginzburg–Landau theory predicts that $\upsilon=0.5$, $z=2$ and $\eta=0$. Thus, as predicted by Aslamazov and Larkin,[13] for $d=3$ the conductivity exponent is $\lambda=0.5$, which reproduces the value experimentally found in the λ_G regime. From the critical amplitude for this regime, given by[14]

$$A = e^2/32\hbar\xi_c(0), \tag{6}$$

where the planar anisotropy of YBCO was taken into account, we may extract the coherence length perpendicular to the layered structure, $\xi_c(0)$. We list in Table I the values for $\xi_c(0)$ deduced from our data. Since this quantity does not show a clear dependence with P, we estimate that $\xi_c(0) = 0.13(\pm 0.02)$ nm in the studied range. This value is in reasonable agreement with the most accepted estimations for this quantity.[15,7] Thus, both the exponent and amplitude values found for $\Delta\sigma$ in the region characterized by λ_G lead us to interpret this regime as resulting from 3D-G fluctuations. The fact that $\xi_c(0)$ does not change with P is not entirely surprising in view of the weak sensitivity of T_c and other superconducting properties to pressure applied along the c axis in YBCO.[2,16,17]

We interpret the narrow linear region just above $T_c(P)$ in the χ_σ^{-1} results of Fig. 3 as resulting from genuine critical fluctuations. In low applied pressures, the obtained exponent $\lambda_{cr}\cong 0.18$ characterizes a regime "beyond 3D-XY," already observed in YBCO.[18,7] The origin of this fluctuation regime is still unclear. A possibility is that it may be a precursor to a weakly first-order pairing transition. In the highest studied pressure, however, the exponent characterizing the asymptotic fluctuation region is $\lambda_{cr}\cong 0.32$. This is precisely the value expected from the 3D-XY universality class[19] with dynamics given by the model E.[20] These models predict that $\upsilon=0.67$, $\eta=0.03$ and $z=1.5$. The 3D-XY full dynamic scaling was identified in YBCO by several authors.[6,7,12,21] The crossover produced by pressure in the critical fluctuation conductivity of YBCO is similar to that induced by magnetic fields. Indeed, under very low fields the asymptotic critical regime

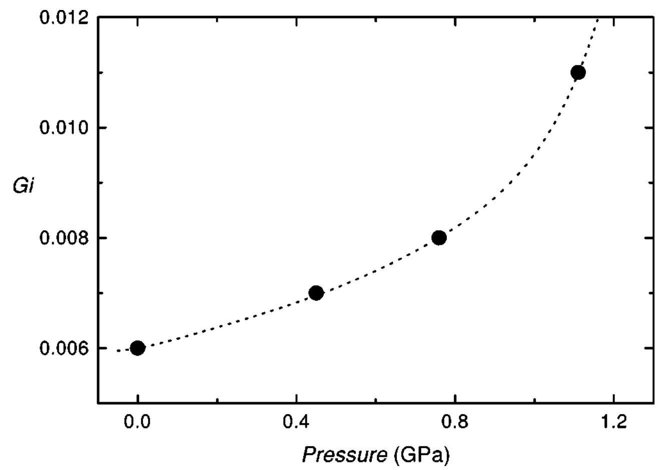

FIG. 4. Ginzburg number as a function of pressure as deduced from results in Fig. 3.

observed in this system is beyond 3D-XY.[7] However, above a certain (low) value of the applied field, this scaling is suppressed and the 3D-XY regime becomes visible. As observed in previous investigations[7,12] the mean-field critical temperature T_c^{mf}, extrapolated from 3D-G regime, as indicated in Fig. 3, is located below T_c, which is extrapolated from the critical regime. This suggests that, contrasting with magnetic transitions, critical superconducting fluctuations tend to increase T_c with respect to the mean-field expectation. Results in Fig. 3 show that T_c^{mf} and T_c increase with pressure at similar rates.

The data in Fig. 3 also allow us to study the pressure effects on the extent of the critical fluctuation regime. This is generally accounted for by the Ginzburg criterium which is related to the breakdown of the mean-field Ginzburg–Landau (GL) theory to describe the superconducting transition.[22] Above T_c, this criterium is identified to the lowest temperature limit for the validity of the Gaussian fluctuation region. In Fig. 3 we denote as T_G the crossover temperature delimiting the Gaussian and critical intervals, and assign this temperature to the intersection between the straight lines fitted to these regimes in the χ_σ^{-1} plots. From T_G and from T_c^{mf} for each applied pressure we calculate the Ginzburg number, given as $Gi=(T_G-T_c^{\mathrm{mf}})/T_c^{\mathrm{mf}}$. Figure 4 shows that Gi increases with P, implying that the genuine critical fluctuations are enhanced when the pressure is augmented. According to the anisotropic GL theory, the Ginzburg number is given as[22,23]

$$Gi = \alpha\left(\frac{k_B}{\Delta c\,\xi_c(0)\xi_{ab}^2(0)}\right)^2, \tag{7}$$

where α is a constant of the order 10^{-3}, Δc is the jump of the specific heat at T_c, and $\xi_{ab}(0)$ is the in-plane coherence length. According to the microscopic theory,[23] $\Delta c \sim T_c N(0)$, where $N(0)$ is the single-particle density of states at the Fermi level. We expect that Δc is weakly P dependent in the studied range since $N(0)$, as deduced from the Pauli susceptibility above T_c, is rather insensible to pressure in the HTSC.[2] On the other hand, our analysis of the 3D-G

fluctuation conductivity amplitude indicates that $\xi_c(0)$ does not change significantly with P. We are thus led to conclude that the appreciable increase of *Gi* with pressure is primarily due to a reduction in $\xi_{ab}(0)$. From Eq. (7) we estimate that a 14% decrease in $\xi_{ab}(0)$ produces the observed enhancement of *Gi* at $P=1.11$ GPa. This conclusion is in accordance with prior findings[2,16,17] showing that the superconducting properties in optimum doped YBCO depend much more on the variation of the atomic distances within the atomic layers than along the c axis.

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