Low Temperature Physics/Fizika Nizkikh Temperatur, 2021, vol. 47, No. 5, pp. 420–423

Influence of uniform compression on fluctuation paraconductivity of single crystals $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$

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Received December 22, 2020, revised January 22, 2021, published online March 26, 2021

The work investigated the effect of high hydrostatic pressure up to 12 kbar on the fluctuation conductivity of medium-doped praseodymium ($x \approx 0.23$) single-crystal $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples. It was found that in contrast to the pure $YBa_2Cu_3O_{7-\delta}$ samples and the $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ samples lightly doped with praseodymium, the application of high pressure leads to a significant decrease in the transverse coherence length ξ_c and an increase in the baric derivative dT_c/dP. Possible mechanisms of the effect of high pressure on the critical temperature and coherence length in the bulk of the experimental sample are discussed.

Keywords: YBaCuO single crystals, doping, hydrostatic pressure, fluctuation conductivity, coherence length.

The study of the dimension of the superconducting fluctuation subsystem continues to be one of the urgent problems that allow shedding light on the microscopic mechanism of the onset of high-temperature superconductivity (HTSC) [1–3]. Indeed, the fluctuation paraconductivity, along with the pseudogap anomaly (PG) [4, 5], metal-insulator transitions [6, 7], and incoherent electric transport [8, 9], is one of the unusual phenomena observed in HTSC compounds in a normal state, which according to modern concepts are vital for understanding the nature of HTSC (see, for example, [1–3]).

In a reasonably numerous series of HTSC cuprates, a special place for research, in this aspect, is occupied by the compound of the 1-2-3 system with partial replacement of yttrium with praseodymium [10, 11], which is due to several reasons at once. First, the compounds of the 1-2-3 system have a sufficiently high critical temperature (T_c), which allows measurements at temperatures exceeding the temperature of liquid nitrogen [12]. Second, partial replacement of yttrium with praseodymium, in contrast to replacement with other rare earth elements, allows smoothly varying the electrical resistance and critical characteristics of this compound by gradually suppressing their conducting parameters [10, 13, 14] (the so-called praseodymium anomaly). Thirdly, in the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds with the optimal oxygen content [10, 14], the so-called nonequilibrium state does not arise, which in pure oxygen-deficient $YBa_2Cu3O_{7-\delta}$ samples can be easily induced by a jump in temperature [15, 16] or application of high pressure [17, 18].

The latter circumstance is significant since the most convenient tool that allows one to directly influence the dimension of the fluctuation subsystem is precisely the application of high pressure [19, 20]. In this condition, in the case of pure samples, specific methods are used to separate the so-called true pressure effect [21, 22] (caused by the parameters of the crystal lattice of interlayer interaction, phonon interaction, etc.) and the relaxation effect [17, 18] (due to the redistribution of the labile component). Despite a fairly large number of works, in the literature on the study of the effect of pressure on the conductivity of the HTSC the main attantion was paid to the study of the pressure dependences of the resistive characteristics of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds (see [10] and references therein). At the same time, we did not find works devoted to studies of fluctuation conductivity under high pressure in these compounds.

Considering the above, in this work, we studied the effect of high hydrostatic pressure up to 12 kbar on the fluctuation paraconductivity of medium-doped with praseodymium ($x \approx 0.23$) single-crystal $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples.

HTSC single crystals of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds were grown by solution-melt technology in a gold crucible, according to the method described in our work [20], which presented the results of studies of the effect of hydrostatic pressure on the critical temperature of these samples. For resistive studies, rectangular crystals with a size of 3×0.5×0.03 mm were selected. The smallest crystal size corresponded to the c axis direction. Electrical contacts were created according to a standard 4-contact scheme by applying a silver paste to the crystal surface, followed by connecting silver conductors 0.05 mm in diameter and annealing for three hours at a temperature of 200 °C in an oxygen atmosphere. This procedure made it possible to obtain a contact resistance of less than one Ohm and to carry out resistive measurements at transport currents up to 10 mA in the *ab* plane. Hydrostatic pressure was created in a piston-cylinder multiplier [18]. The pressure value was determined using a manganin manometer, and the temperature was determined with a copper-constantan thermocouple mounted in the outer surface of the chamber at the level of the sample position.

Figure 1 shows the temperature dependences of the electrical resistivity in the *ab* plane, measured at different pressures. Insets (a) and (b) show resistive transitions to the superconducting state in the coordinates ρ_{ab} vs T and $d\rho_{ab}(T)/dT$ vs T, respectively. As can be seen from Fig. 1 and the inserts to it, the critical temperature increases with an increase in the applied pressure at a rate of $dT_c/dP \approx 0.3$ K/kbar, which is somewhat less than for compounds with $x \geq 0.1$ [10], but more than for pure single crystals $YBa_2Cu_3O_{7-\delta}$ [21, 22]. It is also seen from Fig. 1 that the qualitative behavior of the temperature dependence of the conductivity in all cases is quasi-metallic. With an increase in pressure, the absolute value of the electrical resistance decreases, and the region of existence of the linear dependence $\rho_{ab}(T)$ at high temperatures slightly expand, which may indicate a corresponding narrowing of the temperature region of the realization of the PG anomaly [4, 5].

As can be seen from Fig. 1, below a certain characteristic temperature T^* the dependences *ab*(*T*) "round off", which may be due to the appearance of excess conductivity, the temperature dependence of which can be obtained by the formula:

$$\Delta\sigma = \sigma - \sigma_0, \qquad (1)$$

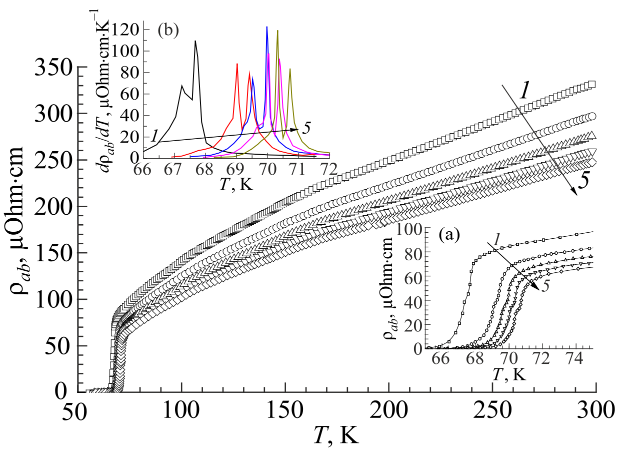

Fig. 1. The temperature dependences of the electrical resistivity in the basal plane $\rho_{ab}(T)$ of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal measured at pressures, kbar: 0 (*1*); 4.1 (*2*); 6.4 (*3*); 8.7 (*4*); 11 (*5*). Inserts (a) and (b): resistive transitions to the superconducting state in the coordinates ρ_{ab} vs T and $d\rho_{ab}(T)/dT$ vs T.

where $\sigma_0 = \rho_0^{-1} = (A + BT)^{-1}$ is the conductivity determined by interpolation of the linear section observed in the high-temperature measurement region to the zero-temperature value (A and B — numerical coefficients), and $\sigma = \rho^{-1}$ is the experimentally measured conductivity value at $T < T^*$. It is known that near T_c the excess conductivity is probably due to the processes of fluctuation pairing of current carriers and can be described by the power dependence obtained in the theoretical Lawrence–Doniach model [23], which assumes the presence of a very smooth crossover from two-dimensional to three-dimensional fluctuation conductivity with decreasing sample temperature:

$$\Delta\sigma = \left[\frac{e^2}{16\hbar d}\right]\varepsilon^{-1}\left\{1 + J\varepsilon^{-1}\right\}^{-1/2}, \qquad (2)$$

where $\varepsilon = (T - T_c^{mf})/T_c^{mf}$ is reduced temperature; T_c^{mf} is the critical temperature in the mean-field approximation; $J = (2\xi_c(0)/d)^2$ is interplanar pairing constant; ξ_c is the coherence length along the c axis and d is the thickness of the two-dimensional layer. In limited situations (near T_c, at $\xi_c >> d$, where the interaction between fluctuating Cooper pairs is realized in the entire volume of the superconductor, i.e., the 3D mode or far from T_c, at $\xi_c << d$, where the interaction is possible only in the planes of the conducting layers, i.e., 2D mode), expression (2) is transformed into the known relations for three- and two-dimensional cases from the Aslamazov–Larkin theory [24]:

$$\Delta\sigma_{2D} = \frac{e^2}{16\hbar d}\varepsilon^{-1}, \qquad (3)$$

$$\Delta\sigma_{3D} = \frac{e^2}{32\hbar\xi_c(0)}\varepsilon^{-1/2}. \qquad (4)$$

In the case of comparison with experimental data, it is essential to accurately determine the value of T_c^{mf}, which significantly affects the slope of the dependences $\Delta\sigma(\varepsilon)$. Usually, when compared with the experimental data, $\xi_c(0)$, d, and T_c in Eqs. (2)–(4) are adjustable parameters [25]. However, when using this technique, as a rule, there are significant quantitative discrepancies between theory and experiment. This, in turn, necessitates the use of a scaling factor, the so-called C factor, as an additional adjustable parameter, which makes it possible to combine experimental data with calculated ones and, thus, take into account the possible inhomogeneity of the spreading of the transport current for each specific sample. In our case, T_c^{mf} was taken to be T_c, determined, as noted above, at the maximum point in the $d\rho_{ab}/dT(T)$ dependences in the superconducting transition region, as was proposed in [19] and shown in the inset (b) to Fig. 1.

Figure 2 shows the temperature dependences of $\Delta\sigma(T)$ in the coordinates $\ln\Delta\sigma(\ln\varepsilon)$. It can be seen that near T_c these dependencies are satisfactorily approximated by straight lines with an inclination angle $\alpha_1 \approx -0.5$, corresponding

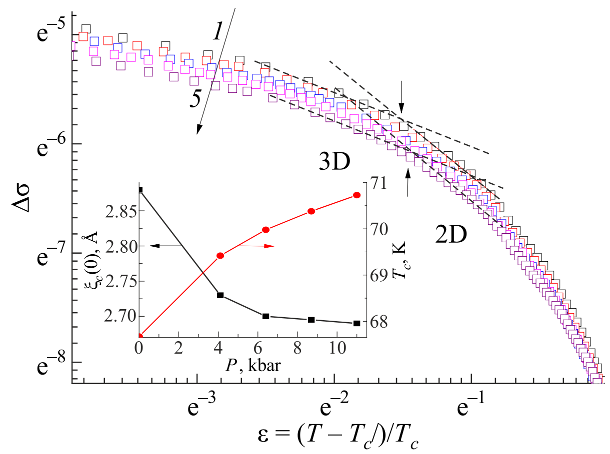

Fig. 2. (Color online) Temperature dependences $\Delta\sigma(T)$ in coordinates $\ln\Delta\sigma\,(\ln\varepsilon)$ at different pressures. The numbering corresponds to Fig. 1. The vertical arrows show the position of the 3D–2D crossover points. Inset shows the pressure dependences $T_c(P)$ and $\xi_c(P)$.

to the exponent –1/2 in Eq. (4), which indicates the three-dimensional nature of fluctuating superconductivity in this temperature range. With a further increase in temperature, the rate of decrease in $\Delta\sigma$ significantly increases ($\alpha_2 \approx -1$), which, in turn, can be considered as an indication of a change in the FP dimension. As follows from (3) and (4), at the 2D–3D crossover point:

$$\varepsilon_0 = 4\left[\xi_c(0)/d\right]^2. \qquad (5)$$

In this case, having determined the value of ε_0 and using the literature data on the dependence of T_c and the interplanar distance on δ [26, 27], we can calculate the values of $\xi_c(0)$. As can be seen from the inset to Fig. 2, the value of $\xi_c(0)$, calculated according to (5), decreases from 2.88 Å to 2.69 Å as T_c increases, which qualitatively differs from the analogous pressure dependences $\xi_c(0)$ obtained as for pure YBaCuO samples of optimum composition [19, 28], and single crystals lightly doped with praseodymium [11]. As was established in [19, 28], the value of $\xi_c(0)$ obtained for crystals optimally doped with oxygen changes insignificantly with pressure. At the same time, for single crystals lightly doped with praseodymium [11], the value of $\xi_c(0)$ increases with an increase in the applied pressure from 0 to 17 kbar by approximately 15 %. It should also be noted that in our case there is a clear correlation in the behavior of the pressure dependences $\xi_c(P)$ and $T_c(P)$ obtained during the application of high pressure (see the inset to Fig. 2). Both values change almost symmetrically, as $T_c(P)$ increases, the $\xi_c(P)$ value decreases and vice versa, which may indicate the same nature of the change in these characteristics. The change in T_c under the influence of pressure can be caused by a change in the constant of the electron-phonon interaction and the concentration of current carriers. The latter, in turn, implies a change in the density of states at the Fermi level $N(E_F)$: an increase in pressure leads to an increase in $N(E_F)$, while a decrease leads to a decrease in $N(E_F)$.

Table 1 shows the numerical values of the experimental parameters of the test sample [resistivity ρ_{300} at 300 K, critical temperature T_c, PG opening temperature T^*, reduced temperature of the 2D–3D crossover ε_0, crossover temperature T_{cr}, coherence length $\xi_c(0)$] depending on pressure.

Table 1. Experimental parameters of the sample

P, kbar	0	4.1	6.4	8.7	11
ρ_{300}, μΩcm	333.3	298.5	277.4	260.4	250.1
T_c, K	67.67	69.42	69.98	70.38	70.73
T^*, K	167.77	165.7	161.15	155.72	151.4
ε_0	0.2424	0.2178	0.2130	0.2122	0.2114
T_{cr}, K	84.07	84.54	84.87	85.32	85.685
$\xi_c(0)$, Å	2.88	2.73	2.7	2.695	2.69

As we have already noted in [20], the relatively weak effect of pressure on the value of T_c and ξ_c of optimally doped samples can be explained within the framework of the model assuming the presence of a Van Hove singularity in the spectrum of charge carriers [29, 30], which is characteristic of lattices with strong coupling. As is known, for crystals with $T_c \approx 90$ K the Fermi level lies in the valley between two peaks of the density of states, while the density of states at the Fermi level $N(E_F)$ depends significantly on the difference $(a - b)/a$ [29, 30]. An increase in the $(a - b)/a$ ratio leads to an increase in the distance between the peaks of the density of states and, accordingly, to a decrease in $N(E_F)$ and T_c. A decrease in the ratio $(a - b)/a$ leads to the convergence of the peaks of the density of states, which leads to an increase in $N(E_F)$ and T_c. Such regularity of the change in T_c was observed when studying the effect of uniaxial compression along a and b axes on the critical temperature of single crystals with $T_c \approx 90$ K [31]: when a load was applied along the a axis, the critical temperature increased, and when a load was applied along the b axis, it decreased. Under the influence of hydrostatic pressure, the value of the ratio $(a - b)/a$ changes only slightly, since it is determined only by the difference in the compression moduli along the a and b axes. Therefore, the change in the critical temperature under the influence of hydrostatic pressure is relatively small.

For crystals with a reduced $T_c < 70$ K, the Fermi level can be shifted from the middle of the band (also due to doping with substitutional elements [32]) and is located away from the peak of the density of states. Therefore, if the value of the critical temperature is principally determined by the density of electronic states, then the shift of the Fermi level towards the peak of the density of states under the action of hydrostatic pressure can, thereby, lead to a significant increase in the absolute value of dT_c/dP and $\xi_c(0)$. However, checking the validity of this assumption requires additional studies of the effect of uniform compression on the critical temperature of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds, including a broader range of praseodymium concentrations. In this case, one should take into account the fact that specific mechanisms of quasiparticle scattering [33–35], due to the presence of kinematic and structural anisotropy in the system, can play a specific role here.

1. T. Timusk and B. Statt, *Rep. Prog. Phys.* **62**, 161 (1999).
2. J. Ashkenazi, *J. Supercond. Nov. Magn.* **24**, 1281 (2011).
3. R. V. Vovk and A. L. Solovyov, *Fiz. Nizk. Temp.* **44**, 111 (2018) [*Low Temp. Phys.* **44**, 81 (2018)].
4. M. V. Sadovskii, I. A. Nekrasov, E. Z. Kuchinskii, Th. Pruschke, and V. I. Anisimov, *Phys. Rev. B* **72**, 155105 (2005).
5. R. V. Vovk, M. A. Obolenskii, A. A. Zavgorodniy, I. L. Goulatis, A. Chroneos, and E. V. Biletskiy, *J. Alloys Compd.* **485**, 121 (2009).
6. K. Widdera, D. Bernera, H. P. Geserich, W. Widderb, and H. F. Braunb, *Physica C* **251,** 274(1995).
7. R. V. Vovk, Z. F. Nazyrov, I. L. Goulatis, and A. Chroneos, *Physica C* **485**, 89 (2013).
8. P. W. Anderson, *Phys. Rev. Lett.* **67**, 2092 (1991).
9. R. V. Vovk, N. R. Vovk, O. V. Shekhovtsov, I. L. Goulatis, and A. Chroneos, *Supercond. Sci. Technol.* **26**, 085017 (2013).
10. M. Akhavan, *Physica B* **321**, 265 (2002).
11. A. L. Solovjov, L. V. Omelchenko, E. V. Petrenko, R. V. Vovk, V. V. Khotkevych, and A. Chroneos, *Sci. Rep.* **9**, 20424 (2019).
12. M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu, *Phys. Rev. Lett.* **58**, 908 (1987).
13. R. V. Vovk, N. R. Vovk, G. Ya. Khadzhai, I. L. Goulatis, and A. Chroneos, *Solid State Commun.* **190**, 18 (2014).
14. R. V. Vovk, N. R. Vovk, G. Ya. Khadzhai, and O. V. Dobrovolskiy, *Solid State Commun.* **204**, 64 (2015).
15. M. A. Obolenskii, A. V. Bondarenko, R. V. Vovk, and A. A. Prodan, *Fiz. Nizk. Temp.* **23**, 1178 (1997) [*Low Temp. Phys.* **23**, 882 (1997)].
16. A. L. Solovjov, E. V. Petrenko, L. V. Omelchenko, R. V. Vovk, I. L. Goulatis, and A. Chroneos, *Sci. Rep.* **9,** 9274 (2019).
17. D. D. Balla, A. V. Bondarenko, R. V. Vovk, M. A. Obolenskii, and A. A. Prodan, *Fiz. Nizk. Temp.* **23**, 1035 (1997) [*Low Temp. Phys.* **23**, 777 (1997)].
18. A. L. Solovjov, L. V. Omelchenko, R. V. Vovk, O. V. Dobrovolskiy, Z. F. Nazyrov, S. N. Kamchatnaya, and D. M. Sergeyev, *Physica B* **493**, 58 (2016).
19. L. M. Ferreira, P. Pureur, H. A. Borges, and P. Lejay, *Phys. Rev. B* **69**, 212505 (2004).
20. G. Khadzhai, A. Matsepulin, and R. Vovk, *Fiz. Nizk. Temp.* **47**, 184 (2021), [*Low Temp. Phys.* **47**, 166 (2021)].
21. R. Griessen, *Phys. Rev. B* **36**, 5284 (1987).
22. R. V. Vovk, N. R. Vovk, G. Ya. Khadzhai, I. L. Goulatis, and A. Chroneos, *Physica B* **422** 33 (2013).
23. W. E. Lawrence and S. Doniach, *Proceedings of the 12th International Conference on Low Temperature Physics, Kyoto, Japan, 1970*, E. Kanda (ed.), Keigaku, Tokyo (1970), p. 361.
24. L. G. Aslamazov and A. I. Larkin, *FTT* **10**, 1104 (1968) in Russian.
25. T. A. Friedman, J. P. Rice, John Giapintzakis, and D. M. Ginzberg, *Phys. Rev. B* **39**, 4258 (1989).
26. G. D. Chryssikos, E. I. Kamitsos, J. A. Kapoutsis, A. P. Patsis, V. Psycharis, A. Koufoudakis, Ch. Mitros, G. Kallias, E. Gamari-Seale, and D. Niarchos, *Physica C* **254**, 44 (1995).
27. R. V. Vovk, M. A. Obolenskii, Z. F. Nazyrov, I. L. Goulatis, A. Chroneos, and V. M. Pinto Simoes, *J. Mater Sci.: Mater. Electron.* **23**, 1255 (2012).
28. R. V. Vovk, M. A. Obolenskii, A. A. Zavgorodniy, A. V. Bondarenko, I. L. Goulatis, A. V. Samoilov, and A. I. Chroneos, *J. Alloys Compd.* **453**, 69 (2008).
29. V. M. Gvozdicov, *Physica C* **235–240**, 2127 (1994).
30. A. Perali and G. Varelogiannis, *Phys. Rev. B* **61**, 3672 (2000).
31. U. Welp, M. Grimsditch, S. Flesher, W. Nessler, J. Downey, G. W. Crabtree, and J. Guimpel, *Phys. Rev. Lett.* **69**, 2130 (1992).
32. U. Schwingensclogl and C. Schuster, *Appl. Phys. Lett.* **100**, 253111 (2012).
33. O. V. Dobrovolskiy, V. M. Bevz, M. Yu. Mikhailov, O. I. Yuzephovich, V. A. Shklovskij, R. V. Vovk, M. I. Tsindlekht, R. Sachser, and M. Huth, *Nat. Commun.* **9**, 4927 (2018).
34. N. Kuganathan, P. Iyngaran, R. Vovk, and A. Chroneos, *Sci. Rep.* **9**, 4394 (2019).
35. O. V. Dobrovolskiy, R. Sachser, T. Brächer, T. Fischer, V. V. Kruglyak, R. V. Vovk, V. A. Shklovskij, M. Huth, B. Hillebrands, and A. V. Chumak, *Nat. Phys.* **15**, 477 (2019).

Вплив всебічного стискання на флуктуаційну парапровідність монокристалів $Y_{0.77}Pr_{0.23}Ba_2Cu_3O_{7-\delta}$

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Досліджено вплив високого гідростатичного тиску до 12 кбар на флуктуаційну провідність середньодопованих празеодимом ($x \approx 0.23$) монокристалічних зразків $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$. Виявлено, що, на відміну від бездомішкових зразків $YBa_2Cu_3O_{7-\delta}$ та зразків $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$, слабколегованих празеодимом, прикладання високого тиску призводить до суттєвого зменшення величини поперечної довжини когерентності ξ_c та збільшення баричної похідної dT_c/dP. Обговорюються можливі механізми впливу високого тиску на критичну температуру і довжину когерентності в об'ємі експериментального зразка.

Ключові слова: монокристали YBaCuO, допування, гідростатичний тиск, флуктуаційна провідність, довжина когерентності.