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Effect of high pressure on conductivity in the basal plane of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals lightly doped of praseodymium

***G.Ya.Khadzhai*[1], *N.R.Vovk*[1], *R.V.Vovk*[1,2], *S.V.Savich*[1], *M.Kislitsa*[1], *K.A.Kotvitskaya*[1,2], *V.S.Morozov*[2], *J.G.Leniv*[2], *S.S.Timofeev*[2]**

[1]Physics Department, V.Karazin Kharkiv National University,
4 Svobody Sq., 61022 Kharkiv, Ukraine
[2]Ukrainian State Academy of Railway Transport,
7 Feyerbaha Sq., 61050 Kharkiv, Ukraine

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Effect of high hydrostatic pressure up to 17 kbar on conductivity of lightly Pr-doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($x \approx 0.05$) single crystals is investigated. We show that in contrast to non-doped $YBa_2Cu_3O_{7-\delta}$ samples, application of the high pressure leads to a substantial increase of the pressure derivative of the coherence length $d\xi_c/dP$ and temperature shift of 2D-3D crossover point. Possible mechanisms of the influence of the high pressure on the critical temperature and the coherence length are discussed within the frames of a model assuming the presence of singularities in the charge carriers electron spectrum typical for lattices with strong coupling. The excess conductivity $\Delta\sigma(T)$ in $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ has been revealed to obey an exponential dependence in the wide temperature range $T_f < T < T^*$. At this, description of the excess conductivity by the expression $\Delta\sigma \sim (1 - T/T^*)\exp(\Delta^*_{ab}/T)$ can be interpreted in terms of the mean-field theory, where T^* is the mean-field superconducting transition temperature and pseudogap temperature dependence is satisfactory described within the framework of the BCS-BEC crossover theory. An increase of the applied pressure leads to narrowing of the temperature range of realization of the pseudogap regime, thereby expanding the linear temperature dependence of the basal-plane resistivity $\rho_{ab}(T)$.

Keywords: YBCO single crystals, doping, hydrostatic pressure, fluctuation conductivity, crossover, fluctuation conductivity, pseudogap state.

Исследовано влияние высокого гидростатического давления до 17 кбар на проводимость в базисной *ab*-плоскости слабо допированных празеодимом ($x \approx 0.05$) монокристаллических образцов $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ с системой однонаправленных двойниковых границ. Обнаружено, что, в отличие от беспримесных образцов $YBa_2Cu_3O_{7-\delta}$, приложение высокого давления приводит к существенному возрастанию величины барических производных dT_c/dP и $d\xi_c/dP$ и смещению по температуре точки 2D-3D кроссовера. Обсуждаются возможные механизмы влияния высокого давления на критическую температуру и длину когерентности в объеме экспериментального образца в рамках модели, предполагающей наличие сингулярностей в электронном спектре носителей заряда, который характерен для решеток с сильной связью. Установлено, что избыточная проводимость $\Delta\sigma(T)$ монокристаллов $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ в широком интервале температур $T_f < T < T^*$ подчиняется экспоненциальной температурной зависимости. При этом описание избыточной проводимости с помощью соотношения $\Delta\sigma \sim (1 - T/T^*)\exp(\Delta^*_{ab}/T)$ может быть интерпретировано в терминах теории среднего поля, где T^* представлена как среднеполевая

температура сверхпроводящего перехода, а температурная зависимость псевдощели удовлетворительно описывается в рамках теории кроссовера БКШ-БЭК. Увеличение прилагаемого давления приводит к эффекту сужения температурного интервала реализации ПЩ-режима, тем самым расширяя область линейной зависимости $\rho(T)$ в *ab*-плоскости.

Вплив високого тиску на провідність у базисній площині слабко легованих празеодимом монокристалів $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$. *Г.Я. Хаджай, М.Р. Вовк, Р.В. Вовк, С.В. Савич, М. Кислиця, К.А. Котвицька, В.С. Морозов, Я.Г. Ленів, С.С. Тимофєєв*

Досліджено вплив високого гідростатичного тиску до 17 кбар на провідність у базисній *ab*-площині слабо допованих празеодимом ($x \approx 0.05$) монокристалічних зразків $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ з системою односпрямованих двійникових меж. Виявлено, що, на відміну від бездомішкових зразків $YBa_2Cu_3O_{7-\delta}$, прикладання високого тиску приводить до істотного зростання величини баричних похідних dT_c/dP і $d\xi_c/dP$ і зміщення за температурою точки 2D-3D кросовера. Обговорюються можливі механізми впливу високого тиску на критичну температуру і довжину когерентності в об'ємі експериментального зразка у рамках моделі, що передбачає наявність сингулярностей в електронному спектрі носіїв заряду, який характерний для решіток з сильним зв'язком. Встановлено, що надлишкова провідність $\Delta\sigma(T)$ монокристалів $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ у широкому інтервалі температур $T_f < T < T^*$ підпорядковується експоненційній температурній залежності. При цьому опис надлишкової провідності за допомогою співвідношення $\Delta\sigma \sim (1 - T/T^*)\exp(\Delta^*_{ab}/T)$ може бути інтерпретовано у термінах теорії середнього поля, де T^* представлена як средньопольова температура надпровідного переходу, а температурна залежність псевдощілини задовільно описується у рамках теорії кросовера БКШ-БЕК. Збільшення тиску, що прикладається, призводить до ефекту звуження температурного інтервалу реалізації ПЩ-режиму, тим самим розширюючи область лінійної залежності $\rho(T)$ в *ab*-площині.

1. Introduction

Study of unusual features of the normal state is one of the actual problems allowing one to shed light on the microscopic mechanism of occurrence of the high-temperature superconductivity (HTSC) [1–3]. For example, fluctuation paraconductivity [2, 3] alongside with the pseudogap anomaly [3–5], metal-insulator transition [6, 7] and incoherent transport [8, 9] relate to the unusual phenomena inherent to HTSC compounds in the normal state. According to present-day views these phenomena can be the key to understanding the nature of the HTSC, see e.g. [1].

In relatively voluminous series of HTSC cuprates the special place for investigations, in the aspect, is occupied by compounds of 1-2-3 system with partial substitution of yttrium for praseodymium [10, 11]. This is caused by several reasons. Firstly, compounds of the 1-2-3 system have a rather high critical temperature (T_c) allowing for measurements at temperatures above the nitrogen liquefaction temperature [12]. Secondly, a partial substitution of yttrium for praseodymium, in contrast to substitutions by other rare earths, allows for fine tuning the electrical resistance and the critical characteristics of these compounds gradually suppressing their conducting parameters (so-called praseodymium anomaly) [10, 13, 14]. And thirdly, in optimally oxygen-doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds [10, 14] the non-equilibrium state does not occur. By contrast, the non-equilibrium state can easily be induced in substituent-free $YBa_2Cu_3O_{7-\delta}$ samples with oxygen deficit by abrupt temperature change [15, 16] or by applying the high pressure [17, 18].

The latter circumstance is particularly important because in the absence of complete microscopic theory of the high-temperature superconductivity the application of the high pressure continues to be one of the most important tools not only to determine the adequacy of the many theoretical models and for empirical search for ways to improve the critical parameters of the HTSC materials [19, 20]. Thus, in the case of substituent-free samples $YBa_2Cu_3O_{7-\delta}$ it is often necessary to employ specific techniques to distinguish between the "true pressure effect" [21, 22], that is caused by changes in the crystal lattice, interlayer interaction, electron-phonon interaction and so forth, and relaxation effect [17, 18] due to re-distribution of the labile component. Despite rather numerous reports on investigation of the effect of pressure on conductivity in the HTSC cuprates, only a minor portion of these has been devoted to study of pressure dependences of the resistive characteristics of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ com-

pounds, see [10] and references therein. It should be noted that the data presented in these works are often quite contradictory. For example, in [10] reported on registration of both, the positive and negative pressure derivatives, dT_c/dP, and, in some cases, on the sign change of dT_c/dP value, as will be regarded in more detail below. The vast majority of the experimental data was obtained on ceramic, film and textured samples with a very different technological prehistory [10, 23]. In the case of single-crystal samples, the presence of a rather disordered structure of twin boundaries (TBs) [24–26] complicates the situation even more. TBs being two-dimensional extended defects as well as the place of convergence of defects of the lower dimensionality are themselves scattering sites for the normal and fluctuation carriers [27], thereby substantially affecting the charge transfer processes in the experimental sample. It should also be noted that in the bibliography there are few works related to the influence of pressure in compounds with praseodymium concentration $x < 0.1$. It is these lightly praseodymium doped samples in which there are observed interesting phenomena of the pseudogap state suppression and abnormal expansion of the temperature dependence of the linear behavior [28, 29]. It should also be noted that studies on the pseudogap anomalies and fluctuation conductivity at the high pressure in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compounds we could not found.

Given the motivation above, here we report the effect of pressure up to 17 kbar on resistive characteristics of lightly praseodymium doped ($x \approx 0.05$) $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals, with geometry of the transport current applied parallel to TBs, that allows us to minimize the effects of scattering at TBs [26].

2. Experimental

$Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals were grown by solution-melt technology in a gold crucible [28, 29]. For electrical resistance measurements we selected rectangular crystals with dimensions of 3×0.5×0.03 mm^3. The smallest dimension corresponds to c-axis. Electrical contacts were arranged in the standard four-probe geometry. The contacts were created by applying a silver paste on the crystal surface. This was followed by connecting of silver conductors 0.05 mm in diameter and annealing of samples at 200° for three hours in oxygen atmosphere. This

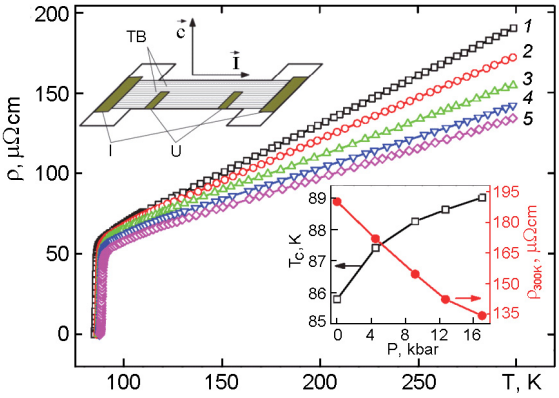

Fig. 1. Temperature dependences of the basal-plane electrical resistivity $\rho_{ab}(T)$ of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal for the following series of pressures: 0; 4.52; 9.17; 12.74; 17.05 kbar, curves *1–5*, respectively. Upper inset: Experimental geometry. Lower inset: Pressure dependence of the critical temperature (left axis) and resistivity at 300 K (right axis).

procedure allowed us to obtain transitional contact resistance of less than 1 Ω and to conduct resistive measurements at transport currents of up to 10 mA in the *ab*-plane. As it is known, when the oxygen saturation occurs in the YBaCuO compounds, there is the tetra-ortho structural transition which, in turn, leads to crystal twinning that minimizes its elastic energy. For the samples with unidirectional twin boundaries, from the crystal it was cut out a bridge with width of 0.2 mm and distance between the voltage contacts of 0.3 mm. Geometry of the experiment was chosen so that the transport current vector I was parallel to TBs [26]. Hydrostatic pressure was created in an cylinder-piston pressure multiplier [18, 22]. Temperature was measured with a copper-constantan thermocouple mounted on the outer surface of the chamber at the sample position level.

3. Results and discussion

Figure 1 shows the temperature dependence of basal-plane resistivity $\rho_{ab}(T)$ in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal for a series of pressures. Upper inset shows the experimental geometry. Lower inset shows pressure dependence of the critical temperature and resistivity at 300 K. As shown in Fig. 1, the values of T_c and $\rho_{ab}(300)$ K at atmospheric pressure are 86 K and 190 μΩcm, respectively. Therefore, in comparison with the non-doped $YBa_2Cu_3O_{7-\delta}$

single-crystal samples the critical temperature is lower by 5–7 K while ρ300 K values are larger by 30–40 μΩcm, that is generally consistent with the literature data [10, 19–22]. In addition to this, step-like peculiarities are observed in the resistive transition to the superconducting state, refer to Fig. 2. These steps may indicate the appearance of phase separation in the sample volume [16, 20].

Currently, there are a number of theoretical models devoted to an explanation of the causes of degradation of the superconducting and the normal-state characteristics of $YBa_2Cu_3O_{7-\delta}$ compounds under the influence of praseodymium impurity. The most known among them are so-called "hole filling model" [30], "pair breaking phenomena" [31], as well as models suggesting the hole carriers localization and various adjustment mechanisms of the band states due to interaction of praseodymium ions (see e.g. [10]). Given the limited volume of our report, these issues will be addressed in more detail in the future study. As follows from the derivative peak shifts in Fig. 1, for our sample there is $dT_c/dP \approx 0.18$ K/kbar.

This value is slightly smaller than those for the compounds with $x \geq 0.1$ [10], but more than that for the non-doped $YBa_2Cu_3O_{7-\delta}$ single crystals [18–22]. In general, the pressure derivative value dT_c/dP can be analyzed relying upon the traditional use of the McMillan formula for $T_c(P)$ dependence [32, 33]:

$$T_c = \frac{\theta_D}{1.45}\exp\left[-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}\right], \quad (1)$$

where θ_D is the Debye temperature, and μ^* is the screened Coulomb pseudopotential describing the electron repulsion, λ is electron-phonon interaction which, in turn, depends on the parameters of electron and phonon spectra of the superconductor

$$\lambda = \frac{N(\varepsilon_F)\langle I^2(\mathbf{k}-(\mathbf{k}')\rangle}{M\theta_D^2}, \quad (2)$$

where $N(\varepsilon_F)$ is density of states at the Fermi level, I is the matrix element of the electron-phonon interaction averaged over the Fermi surface, and M is the ion mass.

Assuming that under the sample compression, along with an increase of the Debye temperature, the matrix element of the electron-phonon interaction increases [34], values of $dT_c/dP < 0.2$ K/kbar seem to be quite reasonable. At the same time, however, it should

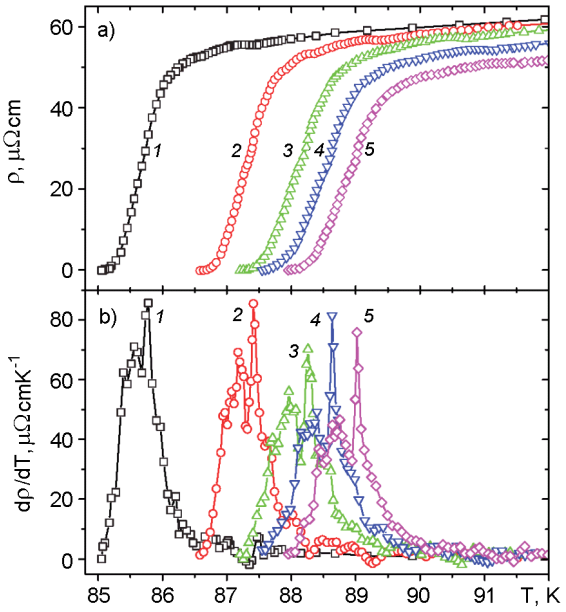

Fig. 2. Resistive transitions to the superconducting state (a) and (b) their temperature derivatives. The curves numbering corresponds to Fig. 1.

be noted that in the samples with praseodymium concentrations of $x > 0.3$ the absolute value of the pressure derivative dT_c/dP could reach more than 0.6 K/kbar [10]. In addition to this, as noted above, some studies reported the sign change in dT_c/P [35]. All the above doesn't allow us to unequivocally interpret the data obtained in the framework of the BCS theory.

The relatively weak effect of pressure on T_c of lightly praseodymium doped samples can be explained by using model implying the presence of the Van Hove singularity in the charge carriers spectrum [36, 37], which is typical for lattices with strong coupling. As it is known, for crystals with high $T_c \approx 90$ K, the Fermi level lies in a valley between two peaks in the states density. Herewith, the states density at the Fermi level $N(E_F)$ essentially depends on so-called orthorhombic distortion $(a-b)/a$ [38]. Specifically, increase of $(a-b)/a$ ratio leads to increase of the distance between the peaks in the states density and, thus, to reduction of $N(E_F)$ and T_c. Reduction of $(a-b)/a$ ratio leads to convergence of the density of the state peaks, which results in increase of $N(E_F)$ and T_c. This pattern of T_c changes was observed when studying the effect of uniaxial compression along a and b axes on the critical temperature T_c of the single crystals with $T_c \approx 90$ K [39]. When the load was applied along a axis, the critical tem-

perature decreased, whereas T_c increased when the load was applied along b axis. When subjected to hydrostatic pressure, the $(a - b)/a$ ratio was changed slightly, since it was determined only by the difference in the bulk moduli along a and b axes. Therefore, the change of the critical temperature T_c in our samples due to the high hydrostatic pressure is qrelatively small. For the crystals with reduced $T_c \approx 60$ K, the Fermi level can be shifted from the middle zone (for instance, in consequence of doping by substitutional elements [40]) and it is situated away from the peak of the states density. Therefore, if the value of the critical temperature is primarily determined by the density of the electronic states, when applying the hydrostatic pressure, the shift of the Fermi level towards the peak of the states density can lead to a significant increase of the absolute value of dT_c/P.

Fig. 2 shows depicting the resistive transitions to the superconducting state in ρ — T and $d\rho/dT$ — T coordinates for a series of pressures. One can distinguish several peaks corresponding to the steps in Fig. 1. As it has been revealed in [41], such a form of the superconducting transition attests to presence of several phases with different critical temperatures T_{c1} and T_{c2} in the sample volume. These temperatures are defined as those corresponding to the maxima of the both peaks. At this, according to the known parabolic law [42], each of these phases is characterized by respective concentration of the charge carriers.

As follows from Fig. 2, the increase of the applied pressure leads to some broadening of the superconducting transition and to change of the height and shape of the steps, as well as to the temperature upshift of the maxima points. This, in turn, can attest to substantial modification of the current passes due to changes in sizes and composition of the clusters with different T_c. In the case of the non-doped $YBa_2Cu_3O_{7-\delta}$, of oxygen non-stoichiometric composition, phenomena of this kind can be observed as a consequence of the ascending diffusion process [18, 41].

As it is seen from Fig. 2, increase of the applied pressure leads to increase of the difference $(T_{c1} - T_{c2})$, which is indicative of the phase segregation in the sample. At the same time, oxygen concentration in the sample is close to the stoichiometric content, that should minimize the effect of labile oxygen re-distribution on the aforementioned processes. Indeed, as it was shown in [17–21], application of the high pressure in the case of stoichiometric $YBa_2Cu_3O_{7-\delta}$ does not, as a rule, initiate structural relaxation processes which usually take place in a consequence of diffusion of the labile oxygen in the sample volume. Apparently that the phase segregation under pressure observed in our case is stipulated by the size change and composition of the clusters characterized by different content of praseodymium [43, 44]. At the same time, it should be noted that increase of praseodymium in the local volume element of the sample leads to an effect which is quite opposite to the effect caused by the increasing oxygen content. Namely, whereas increase of oxygen concentration leads to rise of T_c and an improvement of the conducting characteristics of the single particular phase [2, 3, 16, 41], increase of the praseodymium content results in suppression of the conductivity and decrease of T_c [9, 27]. In this way, by contrast to the case of the non-doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$, samples, the phase segregation observed in the compound $YBa_2Cu_3O_{7-\delta}$, under high pressures appears to be a more complex and mixed process. Accordingly, identification of the more subtle processes requires further investigations of the effect of uniform compression on the critical temperature of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ compound. These investigations should include studies in the broader range of praseodymium concentrations and should be accompanied by structural characterization of the samples with the higher degree of praseodymium doping. Application of pressure also leads to expansion of the linear portion 47 K depending $\rho_{ab}(T)$ at the high temperatures. The latter appears to reduce the magnitude of the temperature T^* at which systematic deviation of the experimental points down from a linear function. According to the modern concepts, T^* corresponds to the pseudogap opening temperature [2, 4], as will be discussed in more detail below.

The sublinear decrease of $\rho_{ab}(T)$ observed at $T < T^*$ attests to appearance of so-called excess conductivity ($\Delta\sigma$) in the crystal. The temperature dependence of the excess conductivity is usually determined as

$$\Delta\sigma = \sigma - \sigma_0, \tag{3}$$

where $\sigma_0 = \rho_0^{-1} = (A + BT)^{-1}$ is the conductivity determined by interpolating the linear section of $\rho(T)$ to zero temperature and

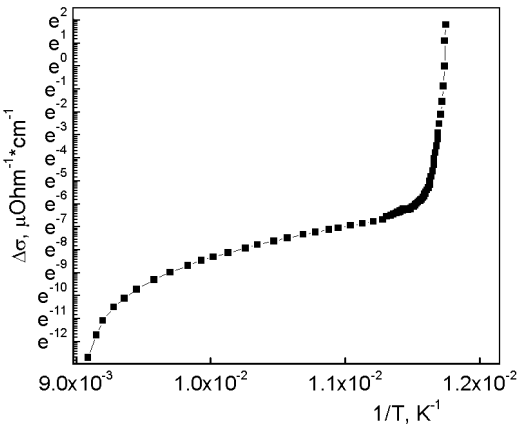

Fig. 3. Inverse temperature dependence of the excess conductivity $\Delta\sigma(1/T)$ of $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ sample at atmospheric pressure in coordinates $\ln\Delta\sigma$ — $1/T$.

$\sigma = \rho^{-1}$ is the experimental value of conductivity in the normal state.

The experimental dependence $\Delta\sigma(T)$ thus obtained at the atmospheric pressure is shown in the inset of Fig. 3 in $\ln\Delta\sigma - 1/T$, representation. One sees that in a rather wide temperature range the curve can be fitted to a straight line, that corresponds to its description by exponential dependence of the form

$$\Delta\sigma \sim \exp(\Delta^*_{ab}/T), \qquad (4)$$

where Δ^*_{ab} is the value determining some thermoactivated process over energy gap — the "pseudogap".

At present, the most argued-for scenarios of the realization of the pseudogap state in the HTSC cuprates refer to so-called conception of uncorrelated pairs [2, 45], as well as various models of dielectric fluctuations [4].

Among the theoretical works standing up for the former viewpoint one should mention the crossover theory from the BCS mechanism to the Bose-Einstein condensation mechanism (BEC) [11]. Specifically, within this BCS-BEC crossover theory there were obtained the pseudogap temperature dependences for the cases of weak and strong coupling. In the general form these dependences described as

$$\Delta(T) = \Delta(0) - \Delta(0)\sqrt{\frac{\pi}{2}}\sqrt{\frac{T}{\Delta(0)}}\exp[-\frac{\Delta(0)}{T}] \times \qquad (5)$$
$$\times\left[1 + \mathrm{erf}\left(\sqrt{\frac{\sqrt{x_0^2+1}-1}{T/\Delta(0)}}\right)\right],$$

where $x_0 = \mu/\Delta(0)$ with μ being the chemical potential of the system of carriers and $\Delta(0)$ the energy gap at $T = 0$, while $\mathrm{erf}(x)$ is the error function.

In the limiting case $x_0 \to \infty$ (weak coupling) expression [11] acquires the form

$$\Delta(T) = \Delta(0) - \Delta(0)\sqrt{2\pi\Delta(0)T}\exp\left[-\frac{\Delta(0)}{T}\right], \qquad (6)$$

which is well known in the BCS theory. In the limiting case of strong coupling in 3D regime ($x_0 < -1$) equation [11] reduces to

$$\Delta(T) = \qquad (7)$$
$$= \Delta(0) - \frac{8}{\sqrt{\pi}}\sqrt{-x_0}\left(\frac{\Delta(0)}{T}\right)^{3/2}\exp\left[-\frac{\sqrt{\mu^2+\Delta^2(0)}}{T}\right].$$

At this, as it was shown in [2, 5, 46], provided measurement accuracy is high enough, the pseudogap values in a wide temperature range can be deduced from the basal-plane electrical resistivity $\rho_{ab}(T)$ at temperatures below some characteristic value T^* called the pseudogap opening temperature. The exponential dependence $\Delta\sigma(T)$ was previously observed in YBaCuO samples [47]. As it was shown in [5, 46, 47], approximation of the experimental data can be substantially expanded by introducing the factor $(1 - T/T^*)$. In this case excess conductivity turns out proportional to the density of superconducting carriers $n_s \sim (1 - T/T^*)$ and inversely proportional to the number of pairs $\sim\exp(-\Delta^*/kT)$, broken down by the thermal motion

$$\Delta\sigma \sim (1 - T/T^*)\exp(\Delta^*_{ab}/T). \qquad (8)$$

At this, T^* is regarded as the mean-field superconducting transition temperature, while the temperature interval $T_c < T < T^*$, in which the pseudogap state exists, is determined by rigidity of the order parameter phase. The latter, in turn, depends on the oxygen deficit. In this way, using methodology proposed in [5, 47], from the experimental curve $\ln\Delta\sigma(1/T)$ one can deduce the temperature dependence $\Delta^*_{ab}(T)$ up to T^*.

Figure 4 presents the temperature dependences of pseudogap in $\Delta^*(T)/\Delta_{max} - T/T^*$ (Δ_{max} is the value of Δ^* on the plateau away from T^*) representation for the same series of pressures. The dashed lines in Fig. 2 show the dependences $\Delta^*(T)/\Delta(0)$ versus T/T^*, calculated by Eqs. (6) and (7) in the mean-field approximation within the framework of the BCS-BEC crossover theory [45]

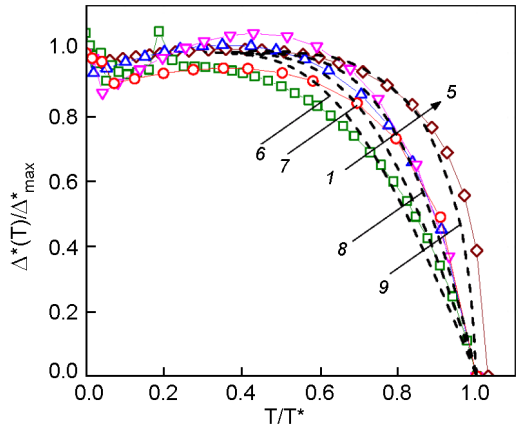

Fig. 4. Temperature dependences of the pseudogap in $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ single crystal in the reduced coordinates $\Delta^*(T)/\Delta^*_{max} - T/T^*(\Delta^*_{max}$ is the value of Δ^* on the plateau away from T^*). The curves numbering corresponds to that in Fig. 1. The dashed lines 5–8 show dependences $\Delta^*(T)/\Delta(0)$ versus T/T^* calculated according to the crossover parameter $\mu/\Delta(0) = 10$ (the BCS limit), −2, −5, and −10 (the BEC limit) [11], respectively.

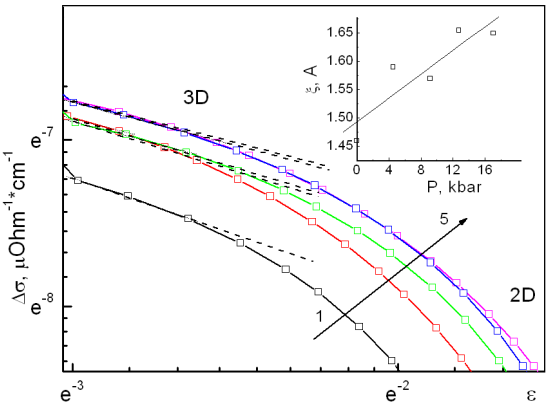

Fig. 5. Temperature dependences $\Delta\sigma(T)$ in coordinates $\ln\Delta\sigma(\ln\varepsilon)$ representation for a series of pressures. The curves numbering corresponds to Fig. 1. Inset: Pressure dependence of the coherence length $\xi_c(0)$.

for the crossover parameter $\mu/\Delta(0) = 10$ (the BCS limit), −2, −5, and −10 (the BEC limit). One sees that as the applied pressure increases, behavior of the curves transits from Eq. (7) to Eq. (6). This behavior is qualitatively similar to the effect of transformation of temperature dependence of the pseudogap in YBaCuO samples upon reducing the level of oxygen nonstoichiometry [5]. Evidently, the mentioned correlations in the behavior of the curves $\Delta^*(T)$ are not occasional. Indeed, as is well known from the literature (see, e.g., [17–21]), application of the high pressure to the HTSC samples from 1-2-3 system, as well as increase of the oxygen content [5] leads to improvement of the conducting characteristics, that becomes apparent through rise of the T_c value and significant reduction of the resistivity. In this way, given some conditionality of determination of the value of the pseudogap opening temperature T^* from downturns of $\rho_{ab}(T)$ curves from the linear dependence, agreement between the experiment and the theory is satisfactory.

As seen from Fig. 3, in the case of approaching T_c the sharp increase in the absolute value of excess conductivity appears. The excess conductivity near T_c is known to be caused by processes of fluctuation pairing of the charge carriers. It can be described by power-law dependence derived in the Lawrence-Doniach model [48]. This model assumes a gradual crossover from two-dimensional (2D) to three-dimensional (3D) regime of the fluctuation conductivity upon decreasing the sample temperature

$$\Delta\sigma = \left[\frac{e^2}{16\hbar d}\right]\varepsilon^{-1}\left\{1 + J\varepsilon^{-1}\right\}^{-1/2}, \qquad (9)$$

where $\varepsilon = (T - T^{mf}_c)/T^{mf}_c$ is the reduced temperature with T^{mf}_c being the critical temperature in the mean-field approximation and $J = (2\xi_c(0)/d)^2$ is the interlayer pairing constant with ξ_c being the coherence length along c-axis and d the thickness of 2D layer. In the limiting cases, 3D regime ensues near T_c, when $\xi_c << d$ and interaction is possible in the planes of the conducting layers. In these limiting cases Eq. (9) reduces to the known expressions in the Aslamazov-Larkin theory [49]

$$\Delta\sigma_{2D} = \frac{e^2}{16\hbar d}\varepsilon^{-1}, \qquad (10)$$

$$\Delta\sigma_{3D} = \frac{e^2}{32\hbar\xi_c(0)}\varepsilon^{-1/2}. \qquad (11)$$

In the case of fitting the experimental data a crucial role is played by accurate determination of the value of T^{mf}_c, which substantially affects the slope angle in $\Delta\sigma(\varepsilon)$. Usually, while comparing $\xi_c(0)$, with the experimental data, d and T_c in Eqs. (9–11) are fitting parameters [50]. However, when such a method is used, one

comes up with considerable discrepancies between the theory and experiment. This in turn substantiates the necessity of using a scaling factor, so-called C-factor, as an additional fitting parameter. This C-factor allows one to fit experimental data to calculated ones and, thereby, to account for possible inhomogeneity of the transport current distribution for each specific sample [50]. In our case for T^{mf}_c we took T_c determined at the derivative maximum in $d\rho_{ab}/dT(T)$ dependences in the superconducting transition region, as it was proposed in [19] and is shown in the inset (b) of Fig. 2.

Figure 5 displays the temperature dependences $\Delta\sigma(T)$ in $\ln\Delta\sigma(\ln\varepsilon)$ representation. One sees that near T_c these dependences are satisfactory approximated by straight lines with a slope of $\alpha_1 \approx -0.5$ corresponding to the exponent $-1/2$ in Eq. (11), that attests to 3D character of the fluctuation conductivity in this temperature range. With the further temperature increase the decrease rate of $\Delta\sigma$ speeds up substantially ($\alpha_2 \approx -1$). This fact can be viewed as signature of the dimensionality change in the fluctuation conductivity. As it follows from Eqs. (10) and (11), in the 2D-3D crossover point

$$\varepsilon_0 = 4\left[\xi_c(0)/d\right]^2. \qquad (12)$$

In this case, having determined the value of ε_0 and using the literature data for the dependence of T_c and interlayer distance on δ [43, 51], one can calculate $\xi_c(0)$. As it is seen in the inset of Fig. 5, the value of $\xi_c(0)$ calculated by Eq. (12) increases from 1.46 to 1.65 ∞ with increasing T_c. This is qualitatively different from the analogous pressure dependences of $\xi_c(0)$ for substituent-free YBCO samples, for the both optimally doped [19, 22] as well as underdoped single crystals [20]. As it was revealed in [19, 22], the value of $\xi_c(0)$ for optimally doped crystals is affected by pressure only slightly. At the same time, in contrast to the samples of stoichiometric composition, for the underdoped crystals the value of $\xi_c(0)$ increases by about 20 % with applied pressure increase from 0 to 10 kbar. It should be also noted that there is a clear correlation between behavior of the pressure dependency $\xi_c(P)$ and $T_c(P)$: during the application depressurizing both quantities vary substantially symmetrically — the growth of $T_c(P)$ value $\xi_c(P)$ is reduced and vice versa, which may indicate change in the same nature of these characteristics. Certain influence in this may have specific mechanisms of the quasiparticle scattering [51,52], due to presence of kinematic and structural anisotropy in the system.

4. Conclusions

In summary, the main results of this work can be summarized as follows. Application of high pressure to $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($x \le 0.05$) single crystals leads to significant expansion of the linear section in dependence $\rho_{ab}(T)$ and to narrowing of the temperature range of the pseudogap state existence. At this, the excess conductivity obeys exponential temperature dependence in a wide temperature range, while the pseudogap temperature dependence is satisfactory described within the framework of the BCS-BEC crossover theory. The evolution upon pressure of the fluctuation conductivity in the lightly Pr-doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals is likely to be determined by two processes: firstly, by general "three-dimensionalizing" of the system in consequence of change of the relation between ξ and d and; secondly, by shift of the Fermi level with respect to the features of the density of states due to the praseodymium doping. Meanwhile, in contrast to the substituent-free $YBa_2Cu_3O_{7-\delta}$ samples, application of the high pressure leads to substantial increase of the pressure derivative dT_c/dP and $d\xi_c/dP$.

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