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# Resistive investigation of pressure effect on the temperature dependence of the pseudogap in $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$ single crystals accounting for the BCS - BEC crossover

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The effect of high hydrostatic pressure on the electrical conductivity, $\sigma(T)$, in the basal *ab* plane of the high-temperature superconductor (HTSC) $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$ single crystals was investigated. It was determined that excess conductivity $\Delta\sigma(T)$ of the studied samples in a certain temperature range $T_f < T < T^*$ are characterized by a modified exponential temperature dependence $\Delta\sigma \sim (1-T/T^*)\exp(\Delta^*_{ab}/T)$, (T* is the mean field temperature of the superconducting transition), which is interpreted in terms of the BCS-BEC crossover theory. An increase in external pressure leads to a narrowing of the temperature range for the existence of a pseudogap (PG) regime, resulting an expansion of the linear temperature dependence of electrical resistivity in the basal *ab* plane.

**Keywords:** excess conductivity; doping; $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals; high-temperature superconductivity; crossover; pseudogap state

**Резистивні дослідження впливу високого тиску на температурну залежність псевдощілини в монокристалах $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$ з врахуванням теорії кросовера БКШ-БЕК.** *Г.Я. Хаджай, І.Л. Гулатіс, О. Хронеос, В.М.П. Сімоес, Р.В. Вовк*

Досліджено вплив високого гідростатичного тиску на поздовжній електропір, $\rho_{ab}$(T), ВТНП-монокристалу $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-\delta}$. Встановлено, що надлишкова провідність $\Delta\sigma(T)$ досліджуваних зразків у певному діапазоні температур $T_f < T < T^*$ характеризується експоненціальною температурною залежністю $\Delta\sigma(T) \sim (1-T/T^*)\exp(\Delta^*ab/T)$, (T*–середньопольова температура псевдощілинного переходу), яка інтерпретується в термінах теорії кросовера BCS-BEC. Збільшення зовнішнього тиску приводить до звуження температурного діапазону існування псевдощілинного режиму, що приводить до розширення лінійної температурної залежності питомого електроопору у базисній ab-площині.

## 1. Introduction

As it has been previously established [1,2], the doping of $YBa_2Cu_3O_{7-\delta}$ compound with substitution elements causes a change in the density of current carriers, thermal and electrical conductivity of this HTSC. Importantly, the properties will depend upon the concentration and type of the impurity [3,4]. In this aspect, it is of particular interest the partial replacement of Y with Pr, which, on the one hand, causes suppression of superconductivity (in contrast to the replacement of Y with other rare earth elements) [1, 2], and on the other hand, allows maintaining virtually unchanged the lattice parameters [5] and the oxygen stoichiometry (i.e. the index δ) [2]. In particular, the study of the influence of Pr on the conditions for the realization of the pseudogap state in Y-Pr-Ba-Cu-O compounds plays an important role not only for clarifying the nature of high-temperature superconductivity, but also for determining ways to increase their critical parameters. We note the certain role of the fact that a significant part of the experimental material was obtained on ceramic, film or textured samples of various technological origins [2,3,6] with a high content of intergranular bonds. As was shown by Prokofyev *et al.* [6], with a sufficiently high measurement accuracy, the pseudogap region in a wide temperature range can be determined by the change in the temperature behavior of the electrical resistivity, $\rho(T)$, in the basal plane below a certain characteristic value T* – the pseudogap opening temperature. In the present study, the effect of Pr impurities ($x \approx 0.34$) on the temperature dependence of the pseudogap in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with different critical temperatures ($T_c$) was investigated under conditions of high hydrostatic pressure up to 10 kbar.

$Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals were grown using the solution-melt technology [1,4]. The initial components for growing the crystals were $Y_2O_3$, $BaCO_3$, $CuO$ and $Pr_5O_{11}$ compounds in the appropriate proportions. The growth and oxygen saturation modes of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ crystals were the same as for undoped single crystals [1]. The electrical resistivity in the ab plane was measured using the standard four-contact technique. The contacts were created by applying silver paste to the crystal surface, followed by attaching silver conductors with a diameter of 0.05 mm and annealing the sample 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 1 Ohm and to carry out resistive measurements at transport currents in the ab plane up to 10 mA. Hydrostatic pressure was created in a piston-type multiplier [7]. The pressure value was determined using a manganin manometer, and the temperature was determined using a copper-constantan thermocouple installed on the outer surface of the chamber at the level of the sample.

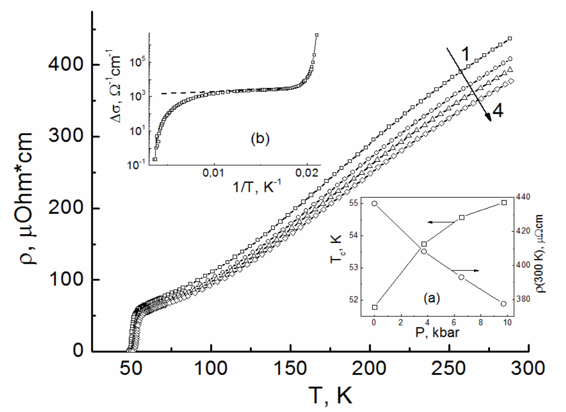


Fig. 1. Temperature dependences of the electrical resistivity in the basal plane, ρ(T), of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal, measured at pressures of 0; 3.72; 6.53; 9.7 kbar – curves *1–4*, respectively. Insert (a): baric dependences of $T_c$ (squares) and ρ(300 K) (circles) of the single crystal. Insert (b): temperature dependence of excess conductivity Δσ(T) of this single crystal at atmospheric pressure.

The temperature dependences of the electrical resistivity $\rho$(T) in the ab-plane of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal are shown in Fig. 1.

As the applied pressure increases, the electrical resistivity of the samples decreases and the critical temperature increases, which is consistent with previous studies [2]. At the same time, it should be noted that all $\rho(T)$ dependences have a section with a characteristic thermal activation deflection. As it can be inferred from Fig. 1, when the sample temperature decreases below T*, $\rho(T)$ deviates downwards from the linear dependence, which indicates the appearance of excess conductivity, that, as noted above, is caused by the transition of the sample to a pseudo-gap mode [1,8]. At the same time, as the applied pressure increases, the interval of the linear dependence $\rho(T)$ narrows significantly – the temperature T* shifts to the region of lower values. This also indicates a corresponding narrowing of the temperature range of the existence of excess conductivity. The temperature dependence of excess conductivity is usually approximated by the equation:

$$\Delta\sigma = \sigma - \sigma_0 \tag{1}$$

where $\sigma_0 = \rho_0^{-1} = (A+BT)^{-1}$ is the normal state conductivity determined by extrapolating the linear section to the low temperature region, and $\sigma = \rho^{-1}$ is the experimental value of the conductivity at low temperatures. As the analysis

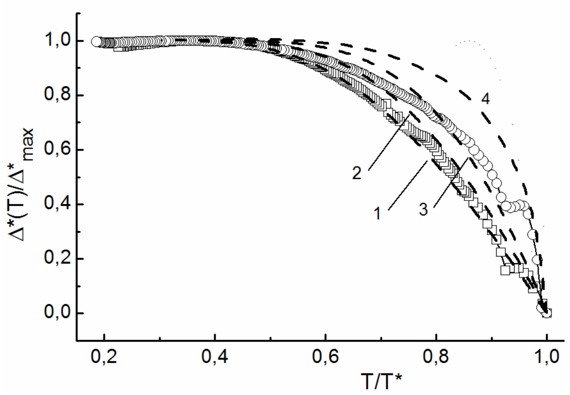


Fig. 2. The temperature dependence of pseudogap in relative coordinates $\Delta^*(T)/\Delta^*_{\text{мax}} - T/T^*$ ($\Delta^*$max is the $\Delta^*$ value on the plateau at a distance of T*) at a pressure of 0 kbar (squares) and 9.7 kbar (circles). The dependences of $\Delta^*(T)/\Delta(0)$ on T/T*, calculated according to [6] for the values of the crossover parameter $\mu/\Delta(0) = 10$ (BCS limit) and –2, –5, – 10 (BEC limit), are shown by dotted lines.

showed, in a fairly wide temperature interval these curves are well described by an exponential dependence of the form:

$$\Delta\sigma \sim \exp(\Delta^*_{ab}/T) \tag{2}$$

were $\Delta^*_{ab}$, is a value that determines a certain thermal activation process associated with the formation of the "pseudogap". The exponential dependence $\Delta\sigma(T)$ has already been observed earlier on film $YBa_2Cu_3O_{7-\delta}$ samples [6]. As it was shown by Prokofyev *et al.* [6], the approximation of experimental data can be significantly expanded by introducing the factor (1–T/T*). In this case, the excess conductivity turns out to be proportional to the density of superconducting carriers, ns ~ (1–T/T*) and inversely proportional to the number of pairs, ~ exp(–Δ*/kT), destroyed by the thermal motion:

$$\Delta\sigma \sim (1-T/T^*)\exp(\Delta^*_{ab}/T) \tag{3}$$

Under this condition, T* is considered as the mean-field temperature of the superconducting transition, and the temperature interval $T_c < T < T^*$, in which the pseudogap state exists and is determined by the rigidity of the order parameter phase, also depends on the oxygen deficiency and/or the concentration of alloying elements. Thus, using the methodology proposed by Prokofiev et al. [6], the temperature dependence of $\Delta^*_{ab}(T)$ can be plotted directly to T* from the experimental curve lnΔσ.

Figure 2 shows the dependence of the pseudogap on temperature in the relative coordinates $\Delta^*(T)/\Delta_{\text{мax}} - T/T^*$ ($\Delta_{\text{мax}}$ is the value of Δ* on the plateau at a distance from T*) at a pressure of 0 kbar and 9.7 kbar.

The temperature dependences of the pseudogap were previously analyzed in [9] within the framework of the BCS-BEC crossover theory. In general, these dependences are described by the equation:

$$\Delta(T) = \Delta(0) - \\ -\Delta(0)\sqrt{\frac{\pi T}{2\Delta(0)}}exp\left[-\frac{\Delta(0)}{T}\right]\left[1+erf\left(\sqrt{\frac{\sqrt{x_0^2+1}-1}{T/\Delta(0)}}\right)\right] \tag{4}$$

where $x_0 = \mu/\Delta(0)$ ($\mu$ is the chemical potential of the charge carrier system; Δ(0) is the energy gap at T = 0), and erf($x$) is the error function.

In the limiting case $x_0 \to \infty$ (weak pairing), the analytical expression (4) takes the form:

$$\Delta(T) = \Delta(0) - \Delta(0)\sqrt{2\pi\Delta(0)T}\,\exp\left[-\frac{\Delta(0)}{T}\right] \tag{5}$$

which is well known from the BCS theory. In the limit of strong interactions in the 3-dimensional case ($x_0 < -1$), equation (4) takes the form:

$$\Delta(T) = \Delta(0) - \frac{8}{\sqrt{\pi}}\sqrt{-x_0}\left(\frac{\Delta(0)}{T}\right)^{\frac{3}{2}}\exp\left[-\frac{\sqrt{\mu^2+\Delta^2(0)}}{T}\right]. \tag{6}$$

In Fig. 2, the dashed lines show the dependences of Δ*(T)/Δ(0) on T/T*, calculated using Eq. (6) for the values of the crossover parameter $\mu/\Delta(0) = 10$ (BCS limit) and –2, –5, –10 (BEC limit). It is evident that with increasing external pressure, the experimental curves shift from the dependences of Eq. (6) to Eq. (5). This behavior is qualitatively similar to the effect of transformation of the temperature dependences of the pseudogap of $YBa_2Cu_3O_{7-\delta}$ samples, which is observed with a decrease in the degree of oxygen nonstoichiometry [6,10,11]. The indicated correlations in the behavior of the Δ*(T) curves are not random. As is known from the literature (see, for example, [1, 10]), the application of external pressure to samples of the HTSC system 1-2-3, as well as an increase in the oxygen content [10, 11] leads to an improvement in the superconducting characteristics, which is expressed in an increase in $T_c$ and a significant decrease in the electrical resistivity. The presence of structural [12-15] and kinematic [16-19] anisotropy in the system may play a role in this. Thus, taking into account some conventionality in determining the pseudogap opening temperature T* by the deviation of the $\rho$(T) dependence from linear behavior, the agreement of theory with experiment in our case can be considered quite satisfactory.

The results of the study indicate the following main conclusions.Firstly, the application of external pressure to $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($x \approx 0.34$) single crystals causes a significant expansion of the interval of the linear dependence $\Delta^*_{ab}(T)$ and a narrowing of the temperature region of the pseudogap regime. Secondly, the excess conductivity $\Delta\sigma(T)$ of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals in a wide temperature range $T_f < T < T^*$ is described by an exponential temperature dependence, and the temperature dependence of the pseudogap is satisfactorily described by the BCS-BEC crossover theory.

## References


1. R.V. Vovk, A.L Solovyov, *Low Temp. Phys.* **44**, 81 (2018)
2. M. Akhavan, *Physica B* **321**, 265 (2002)
3. H.A. Borges and M.A. Continentino, *Solid State Commun.* **80**, 197 (1991)
4. R.V. Vovk, M. A. Obolenskii, A. A. Zavgorodniy, I. L. Goulatis, A. Chroneos, E.V. Biletskiy, *J. Alloys Compd.* **485,** 121 (2009)
5. A.I. Chroneos, I.L. Goulatis and R.V. Vovk, *Acta Chim. Slov.* **54**, 179 (2007)
6. D.D. Prokofyev, M.P. Volkov, Yu.A. Boikov, *Phys. Solid State* **45**, 1168 (2003)
7. A.L. Solovjov, L.V. Omelchenko, E.V. Petrenko, R.V. Vovk, V.V Khotkevych, and A. Chroneos, *Sci Rep* **9,** 20424 (2019)
8. T. Timusk and B. Statt, *Rep. Prog. Phys.* **62**, 61(1999)
9. E. Babaev, H. Kleinert, *Phys. Rev. B.* **159**, 12083 (1999)
10. A.L. Solovjov, L.V. Omelchenko, R.V. Vovk, O.V. Dobrovolskiy, S.N. Kamchatnaya, D.M. Sergeyev, *Curr. Appl Phys.* **16**, 931 (2016)
11. A. L. Solovjov, E. V. Petrenko, L. V. Omelchenko, R.V. Vovk, I. L. Goulatis and A. Chroneos, *Sci Rep* 9: 9274 (2019).
12. Yu.V.Litvinov, G.Ya.Khadzhai, A.V.Samoilov et al., *Funct. Mater.*, **26**, 3, 462 (2019).
13. N.A. Azarenkov, V.N. Voevodin, R.V. Vovk et al., *Funct. Mater.*, **25**, 2, 234 (2018).
14. A.V.Bondarenko, A.A.Prodan, M.A.Obolenskii, R.V.Vovk, T.R.Arouri., *Low Temperature Physics* **27**, N5, 339 (2001).
15. A.V.Bondarenko, V.A.Shklovskij, R.V.Vovk, M.A.Obolenskii, and A.A.Prodan, Low Temp. Phys., 23(12), 962 (1997).
16. R. V. Vovk, C. D. H. Williams, and A. F. G. Wyatt, *Phys. Rev. Lett.* **91**, 235302 (2003).
17. R. V. Vovk, C. D. H. Williams, and A. F. G. Wyatt, *Phys. Rev. B* **68**, 134508 (2003).
18. R. V. Vovk, C. D. H. Williams, and A. F. G. Wyatt, *Phys. Rev. B* **69**, 144524 (2004).
19. R. V. Vovk, C. D. H. Williams, and A. F. G. Wyatt, *Phys. Rev. B* **72**, 054506 (2005).