Pseudogap and fluctuation conductivity in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with different concentrations of praseodymium

A. L. Solovjov, L. V. Omelchenko, R. V. Vovk, and S. N. Kamchatnaya

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Pseudogap and fluctuation conductivity in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with different concentrations of praseodymium

A. L. Solovjov[a)] and L. V. Omelchenko

B. Verkin Physics and Technology Institute for Low Temperatures, NAS Ukraine, 47 Nauka Ave., Kharkov 61103, Ukraine

R. V. Vovk and S. N. Kamchatnaya

V. Karazin Kharkov National University, 4 Svoboda Sq., Kharkov 61077, Ukraine

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The effects of praseodymium doping on the excess conductivity $\sigma'(T)$ and pseudogap (PG) $\Delta^*(T)$ in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals with a change in the Pr concentration from $x = 0$ to $x = 0.43$ are presented. It is found that as x increases the resistance of the samples increases, whereas the critical temperature T_c drops. At the same time the shape of the $\rho(T)$ curves changes from metallic ($x \le 0.34$) to one that is typical for weakly doped $YBa_2Cu_3O_{7-\delta}$ single crystals with a characteristic thermally activated deflection ($x > 0.34$). Regardless of the value of x, close to T_c, $\sigma'(T)$ is well described by the Aslamazov-Larkin and Maki-Thompson theories, demonstrating a 3D-2D crossover with increasing temperature. The crossover temperature T_0 makes it possible to determine the coherence length along the c axis, $\xi_c(0)$. At $x = 0$, $\Delta^*(T)$ displays a maximum at $T_{pair} \approx 110$ K that is typical for YBCO films. As x increases the maximum at T_{pair} is washed out, but a pronounced maximum $\Delta^*(T)$ in the high temperature region appears, followed by a linear section with a positive slope. Such a dependence $\Delta^*(T)$ is normal for magnetic superconductors and is, most likely, caused by the influence of the intrinsic magnetic moment of Pr ($\mu_{Pr} \approx 4\mu_B$). *Published by AIP Publishing.*
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1. Introduction

The study of the pseudogap (PG) continues to be one of the most topical areas in the field of high temperature superconductors (HTSCs).[1–3] Despite the large number of accumulated results, both the nature of the PG and its role in the formation of the superconducting state in HTSCs remain unclear. One of the most interesting materials in the studies pertaining to the PG are $YBa_2Cu_3O_{7-\delta}$ (YBCO) compounds, due to the ability to widely vary their composition by replacing yttrium with isoelectronic analogs or by changing the degree of oxygen non-stoichiometry. Compounds in which there is partial yttrium (Y) substitution with praseodymium (Pr) are of particular interest in this regard. $PrBa_2Cu_3O_{7-\delta}$ (PrBCO) is a dielectric, but isostructural with respect to YBCO.[4,5] In PrBCO charge carriers are localized in the Fehrenbacher-Rice (FR) energy band regardless of oxygen content.[6] Therefore, on the one hand doping $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ (YPrBCO) with praseodymium leads to a gradual suppression of superconductivity with increasing x, but also allows for the preservation of the test sample's lattice parameters and the oxygen index 7-δ (Refs. 7 and 8) on the other.

However, in YPrBCO, the superconducting transition temperature T_c decreases monotonically with increasing x, which is in direct contrast to the nonmonotonic dependence that T_c has on (7-δ) in YBCO.[4] Based on resistive measurements[4,7] and measurements of the Hall effect[4] it follows that at $x \le 0.2$ the YPrBCO single crystal exhibits a behavior that is similar to what is observed in YBCO films. However, at $x \ge 0.3$, the temperature dependence of the resistivity $\rho(T)$ assumes an S-shape that is normal for weakly doped $YBa_2Cu_3O_{7-\delta}$ single crystals with a typical thermally activated deflection,[9] and at $x >$ 0.7 YPrBCO becomes an insulator.[4,7,10] It is believed[5,11] that this occurs as a result of the electron-hole interaction in the Pr 4f-shell, which ultimately leads to the localization of charge carriers in the FR band.[6] As already noted above, the crystal lattice of PrBCO has almost the same dimensions as the crystal lattice of YBCO.[4,5] Therefore, doping with Pr does not lead to noticeable changes in the crystal structure of the sample, or to a change in the oxygen content, which makes it possible to study the HTSC properties directly as a result of the change in the charge carrier density n_f.

This study implements the local pair (LP) model developed by us in Refs. 3 and 12 to investigate the impact Pr has on the temperature dependences of the fluctuation conductivity (FC) and the pseudogap in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals in which the charge carrier density n_f and T_c decrease with increasing concentrations of Pr[5,7,11] over a wide range of concentrations ($0 \le x \le 0.5$). One essential circumstance is the fact that Pr has its own magnetic moment $\mu_{Pr} \approx 3.58\mu_B$[13] and $\mu_{Pr} \approx 2\mu_B$ in the PrBCO compound.[14] Therefore, studying how Pr impurities impact the conditions required for the realization of FC and PG states in such compounds[15,16] plays an important role in elucidating the mechanisms of mutual influence that exist between superconductivity and magnetism in HTSCs, which is very important for the final clarification of the nature of both the PG and high-temperature superconductivity as a whole. The study of the mutual influence of superconductivity and magnetism in HTSCs is one of the most pressing problems in modern condensed matter physics,[1,3] especially after the discovery of iron-containing superconductors.[17]

2. The experiment

The $YBa_2Cu_3O_{7-\delta}$ single crystals were grown using solution-melt technology.[18] In order to obtain crystals in which Y is partially substituted by Pr ($Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$), Pr_5O_{11} was added to the initial charge in the appropriate percentage. The modes of crystal growth and saturation with oxygen were the same as for unalloyed YBCO crystals.[18] Y_2O_3, $BaCO_3$, CuO and Pr_5O_{11} compounds were used as initial components for crystal growth. Samples with dimensions of $1 \times 2 \times 7$ mm were selected for the measurements, wherein the smallest dimension corresponded to the direction along the c axis. Current junctions were mounted from the ends of the sample in order to ensure uniform propagation of the current. Potential contacts were in the form of thin strips across the sample. All junctions were made using silver paste. Resistance in the *ab*-plane was measured by a standard four-probe method at a constant current of up to 10 mA. The temperature of the sample was determined using a platinum thermistor.

The temperature dependences of resistivity $\rho_{ab}(T) = \rho(T)$ in the *ab*-plane of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ multicrystals are shown in Fig. 1. It can be seen that, as noted above, when the Pr content increases the resistance of the samples increases as well while the critical temperature drops, which is in agreement with literature data.[7–11] In this case the $\rho(T)$ curves themselves undergo a transition from the typical metallic to the S-shape that has a characteristically large positive curvature of the experimental curves.[9–11] This type of temperature dependence behavior $\rho(T)$ is also normal for weakly doped YBCO single crystals.[9,19]

According to the theoretical NAFL model (Nearly Antiferromagnetic Fermi-Liquid Model),[20] at high temperatures the linear dependence $\rho(T)$ corresponds to the normal state of the sample that is characterized by the stability of the Fermi surface (FS). Below the characteristic temperature $T^* \gg T_c$ the dependence $\rho(T)$ deviates from the linear one toward lower values, which leads to the appearance of excess conductivity,

$$\sigma'(T) = \sigma(T) - \sigma_N(T) = \left[1/\rho(T)\right] - \left[1/\rho_N(T)\right]. \qquad (1)$$

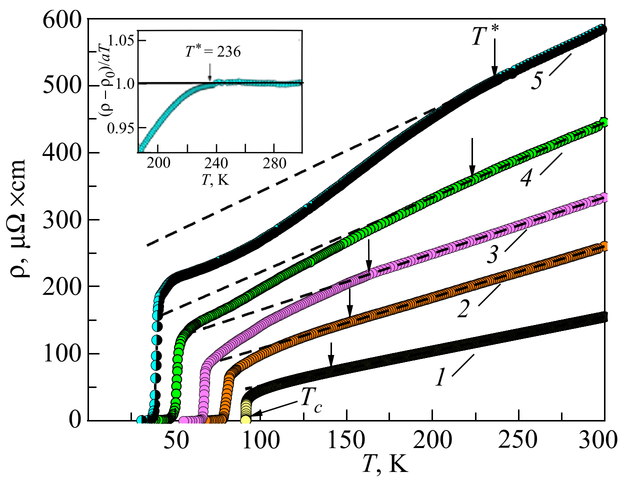

Fig. 1. The temperature dependences of resistivity ρ_{ab} of $Y_{1-x}Pr_xBa_2Cu_3O7-\delta$ single crystals at different praseodymium concentrations x: 0 (1); 0.19 (2); 0.23 (3); 0.34 (4); 0.43 (5). The dashed line is the extrapolation of the normal resistance $\rho_N(T) = aT + \rho_0$ to the low-temperature region. The inset shows the procedure for determining T^* from the dependence $(\rho - \rho_0)/aT = 1$ ($x = 0.43$).

TABLE 1. The parameters of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals.

x	$\rho_{(100K)}$ ($\mu\Omega$ cm)	T_c (K)	T_c^{mf} (K)	T_G (K)	T_0 (K)	T_{01} (K)	ΔT_{fl} (K)	$\xi_c(0)$ (Å)	d_{01} (Å)
0	44.87	91.67	91.73	91.75	91.81	93.9	2.15	0.356	4.12
0.19	98.88	78.52	81.13	81.41	82	84.99	3.58	1.4	6.44
0.23	141.16	66.6	67.5	67.6	68.02	74.03	6.43	1.0	3.18
0.34	197.7	50.53	51.51	51.73	54.4	57.91	6.18	2.77	7.86
0.43	268.46	38.5	39.67	39.9	41.16	46.16	6.26	2.24	5.51

$\rho_N(T) = aT + \rho_0$ gives the sample resistance in the normal state, extrapolated to the low temperature region.[20–24] Accordingly, ρ_0 is determined by the intersection of this linear dependence with the Y axis. T_c was determined by extrapolating the linear part of the resistive transition to the value $\rho(T_c) = 0$. The FC and PG temperature dependences for each single crystal were determined based on excess conductivity analysis. Seven samples with x equal to 0, 0.19; 0.23; 0.34; 0.43; 0.48; 0.5 were studied. However, samples with $x = 0.48$ and $x = 0.5$ demonstrate a thermally activated dependence $\rho(T)$, and are not considered. All samples were analyzed using the LP model developed by us.[3,12] This study considers the results obtained for the $YBa_2Cu_3O_{7-\delta}$ ($x = 0$) sample and praseodymium-doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ at $x = 0.43$, with a subsequent comparison to the results obtained for all other samples. The analysis parameters for all samples are given in Tables 1 and 2.

3. Discussion of the results

3.1. Fluctuation conductivity

The dependence $\sigma'(T)$ calculated according to Eq. (1) in coordinates ln σ' versus ln ε is shown in Fig. 2. wherein (○) is $YBa_2Cu_3O_{7-\delta}$ (a), (◑) is $Y_{0.57}Pr_{0.43}Ba_2Cu_3O_{7-\delta}$ (b). Here $\varepsilon = (T - T_c^{mf}/T_c^{mf}\varepsilon)$ is the reduced temperature and T_c^{mf} (Table I) is the critical temperature in the mean-field approximation[3,25] which is determined by extrapolating the linear section of the σ'^{-2} (T) curve to its intersection with the temperature axis.[3,9,12]

It can be seen that for $x = 0$ in the Ginsburg temperature range $T_G \approx 91.75$ K (ln $\varepsilon_0 \approx -8.2$), up until which $\sigma'(T)$ obeys fluctuation theories,[25,26] and up to the crossover temperature $T_0 \approx 91.81$ K (ln $\varepsilon_0 \approx -6.98$), the experiment is extrapolated well by the fluctuation contribution of the Aslamazov-Larkin theory (AL) for 3D systems:[3,22]

$$\sigma'_{AL3D} = C_{3D}\frac{e^2}{32\hbar\xi_c(0)}\varepsilon^{-1/2} \qquad (2)$$

(the dotted lines 1 on Fig. 2). Respectively, above T_0, up to $T_{01} \approx 93.9$ K (ln $\varepsilon_{01} \approx -3.7$), it is well extrapolated by

TABLE 2. Parameters of pseudogap analysis in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystals.

x	T^*(K)	$\Delta^*(T_c)_{exp}$(K)	$\Delta^*(T_c)_{theor}$(K)	T_{max}(K)	$2\Delta^*(T_c)/kT_c$	ε^*_{c0}
0	141	234	229	110	5	0.14
0.19	152	177.1	173	107	4.4	0.18
0.23	163	166.5	166	105	5	0.43
0.34	223	116	116.2	141	4.6	0.74
0.43	263	97	96.25	226	5	0.6

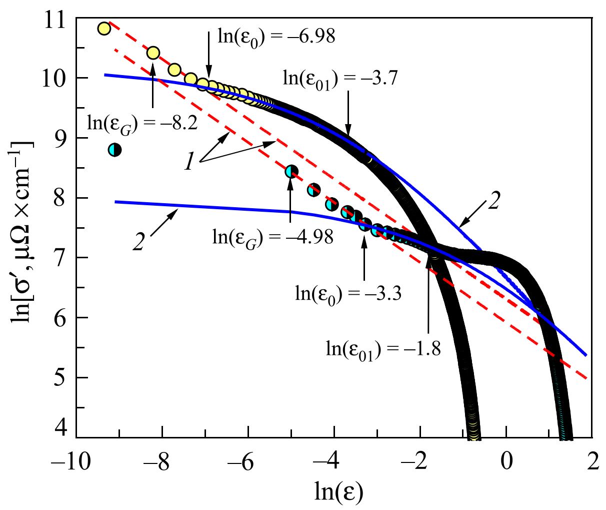

Fig. 2. The dependence of ln σ' on ln ε for $Y_1Ba_2Cu_3O_{7-\delta}$ (○) and $Y_{0.57}Pr_{0.43}Ba_2Cu_3O_{7-\delta}$ (◑) in comparison to fluctuation theories: 1 is the AL contribution; 2 is the MT contribution. The vertical arrows denote the values of ln ε that correspond to T_G, T_0 and T_{01} temperatures.

the Maki-Thompson (MT) fluctuation of the Hikami-Larkin (HL) theory:[23]

$$\sigma'_{\rm MT} = \frac{e^2}{8dh}\frac{1}{1-\alpha/\delta}\ln\left((\delta/\alpha)\frac{1+\alpha+\sqrt{1+2\alpha}}{1+\alpha+\sqrt{1+2\delta}}\right)\varepsilon^{-1} \quad (3)$$

(Fig. 2, solid curve 2). Here $d = c = 11.67$ Å is the size of the YBCO unit cell along the c axis, $\alpha = 2[\xi_c(0)/d]\varepsilon^{-1}$ is the coupling parameter,

$$\delta = \beta\frac{16}{\pi h}\left[\frac{\xi_c(0)}{d}\right]^2 k_B T\tau_\phi \quad (4)$$

is the decoupling parameter, $\tau_\phi \beta T = \pi h/8k_B\varepsilon_0$ is the phase relaxation time of the fluctuation pairs. The multiplier $\beta = 1.203$ (l/ξ_{ab}), wherein l is the mean free path and ξ_{ab} is the coherence length in the ab plane, accounts for the pure limit approximation.[12,23]

The lnσ' (ln ε) dependence for a single crystal with $x = 0.43$ (◑) is also shown on Fig. 2 and is well described by both AL and MT theories. It can be seen that, as is the case for YBCO, at $T = T_0 \approx 41.16$ K (ln $\varepsilon_0 \approx -3.3$) there is a clearly observable dimensional 3D-2D (AL-MT) crossover (Fig. 2), and in the interval ranging from T_0 to $T_{01} \approx 46.16$ K (ln $\varepsilon_{01} \approx -1.8$) the experiment is extrapolated by Eq. (3). Similar dependences of lnσ' (lnε) were obtained for all other samples with the parameters given in Table 1. It can be seen from this table that doping with Pr leads to a significant, almost threefold increase in the temperature interval of superconducting (SC) fluctuations $\Delta T_{fl} = T_{01} - T_G$ with a simultaneous significant (more than six-fold) increase in the coherence length. This is most likely caused by the enhancement of the magnetic interaction in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ with increasing x. It should also be noted that since PrBCO is a dielectric, it forms defects in the conductive matrix of YBCO.[6–8,10,11] This could explain both the sharp increase $\rho(T)$ (Fig. 1) and the nonmonotonic increase in both $\xi_c(0)$ and d_{01} (Table 1) with increasing x.

Thus, we can distinguish four characteristic temperatures on the $\sigma'(T)$ dependence. Let us consider them using the example of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ with $x = 0$. We have $T_c^{\rm mf} = 91.73$ K, below which the region of critical fluctuations in high temperature superconductors is realized[3,23–25] the Ginsburg temperature $T_G = 91.75$ K, up to which the fluctuation theories are valid as the temperature approaches T_c,[25,26] the 3D-2D (AL-MT) crossover temperature $T_0 \approx 91.81$ K (ln $\varepsilon_0 = -6.98$), and $T_{01} \approx 93.9$ K (ln $\varepsilon_{01} = -3.7$). As already noted, the behavior of the HTSC is, to a large extent, determined by the exceptionally short coherence length $\xi_c(T) = \xi_c(0)\ \varepsilon^{-1/2}$, which varies significantly with temperature. Below T_0, near T_c, where $\xi_c(T) > d$, the interaction between the fluctuation Cooper pairs (FCP) occurs across the entire volume of the superconductor. This is the 3D mode. As in, just like all other high-temperature superconductors, near T_c, $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ is three-dimensionalized.[3,12,23,24] Above T_0 we already have $d > \xi_c(T)$. It is obvious that $(T_0) = \xi_c(0)\varepsilon_0^{-1/2} = d$. Therefore, T_0 defines the value $\xi_c(0) = d\sqrt{\varepsilon_0}$.[3,12,23] For $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ with $x = 0$, $T_c = 91.67$, and $T_0 \approx 91.81$, we get $\xi_c(0) = d\sqrt{\varepsilon_0} = 0.356 \pm 0.05$ Å, so, as noted above, $\xi_c(0)$ is very small, which is typical for optimally doped YBCO single crystals.[27] Note that in YBCO ξ_{ab} (0) ~ 15 $\xi_c(0)$,[1–4,9] and in this case ξ_{ab} (0) ≈ 5 Å, i.e., its value is sufficiently reasonable. As the content of Pr increases the value $\xi_c(0)$ increases rapidly (Table 1) which correlates with a decrease in T_c, and at $x > 0.4$ $\xi_c(0)$ assumes values that are typical for weakly doped HTSCs.[1–3,9] Thus, an increase in the concentration of Pr, which, as noted above, does not impact the concentration of oxygen in the sample, leads to almost the same growth in $\xi_c(0)$ as a decrease in YBCO doping with oxygen.

Thus, $\xi_c(T)$ decreases rapidly with an increasing T, and at $T > T_0$, where $\xi_c(T) < d$, the FCP correlation interaction over the entire HTSC volume ceases.[24] However, as before, $\xi_c(T) > d_{01}$, wherein d_{01} is the distance between inner conducting planes CuO_2 in HTSC cuprates.[3,12,23] Therefore, in the $T_0 - T_{01}$ interval $\xi_c(T)$ still connects the CuO_2 planes with Josephson interaction.[23,24] This leads to the formation of two-dimensional FCPs[23,24] at $T > T_0$, which is extrapolated by the 2D MT Eq. (3) (Fig. 2). Finally, at $T > T_{01}$ $\xi_c(T)$ becomes less than d_{01}. As such, all charge carriers are located inside the conducting planes that are now no longer connected by any type of correlation interaction.[23,24] Therefore, as can be seen in Fig. 2, above T_{01} the fluctuation theories do not describe the experiment. Thus, T_{01} determines the region of superconducting fluctuations, $\Delta T_{fl} = T_{01} - T_G$, above T_c. In fact, this is the temperature up to which, according to the theory in Ref. 28, the phase rigidity of the superconducting order parameter Δ is preserved, which is experimentally confirmed.[29,30] In other words, in the T_c–T_{01} interval to a large extent the FCPs behave themselves just like superconducting pairs, but without long-range order (so-called "short-range phase correlations"[28,31,32]).

It is obvious that $\xi_c(T_{01}) = d_{01}$. Accordingly, the equality $\xi_c(0) = d_{01}\sqrt{\varepsilon_{01}} = d\sqrt{\varepsilon_0}$ must be satisfied, which allows us to identify d_{01}, since $\xi_c(0)$ is already known.[3,12] From here we derive that at $x = 0$, $d_{01} = 4.12$ Å (Table 1), which is in good agreement with the data from the $YBa_2Cu_3O_{7-\delta}$ structural measurements, wherein $d_{01} = (3.5–4.5)$ Å.[33,34] However for $x = 0.43$ ($T_c = 38.5$ K and $T_{01} \approx 46.16$ K, ln $\varepsilon_{01} = -1.8$) we obtain $d_{01} = 5.51$ Å. As in, doping with Pr leads to an increase in the effective distance between the conductive planes in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ with increasing x. Simultaneously, as already noted, the SC fluctuation region $\Delta T_{fl} = T_{01} - T_G$ also increases dramatically, from 2.15 K ($x = 0$) to 6.26 K ($x = 0.43$) (Table 1). It should also be noted that above T_{01} the dependence $\sigma'(T)$ deflects upward appreciably, forming a hump above the theoretical MT curve (Fig. 2). A similar dependence $\sigma'(T)$ was observed in the study of the FCPs in an iron-containing magnetic superconductor $EuFeAsO_{0.85}F_{0.15}$.[35] Therefore, it can be argued that since doping with Pr does not lead to a change in the amount of oxygen in the sample, all of the observed effects, including the increase in $\xi_c(T)$, are presumably caused by an increase in the influence of magnetism in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ with an increasing x.

3.2. Analysis of the pseudogap temperature dependence

When analyzing the PG, we assume[1–3,9,12] that the deviation in the resistance of the sample toward smaller values, observable at $T \leq T^*$ (Fig. 1), is due to the formation of local pairs in the HTSC (strongly coupled bosons, SCB), which are subject to the Bose-Einstein condensate (BEC) theory.[31] As the temperature decreases, at $T = T_{pair}$ the local pairs are transformed into fluctuation Cooper pairs that obey the BEC theory.[25] This idea is the main assumption in the LP model.[3] As a result, according to Eq. (1), excess conductivity is manifested in the interval $T^* > T > T_c$, and is defined by equation

$$\sigma'(\varepsilon) = \frac{e^2 A_4 \left(1 - \frac{T}{T^*}\right)\left(\exp\left(-\frac{\Delta^*}{T}\right)\right)}{\left(16\hbar\xi_c(0)\sqrt{2\varepsilon^*_{c0}\,\mathrm{sh}\left(2\varepsilon/\varepsilon^*_{c0}\right)}\right)}, \quad (5)$$

wherein $(1 - T/T^*)$ defines the number of LPs formed at $T \leq T^*$, and $\exp(-\Delta^*/T)$ defines the number of LPs destroyed by fluctuations at $T_{pair} > T > Tc$.[3,12]

Accordingly, the equation for parameter Δ^*, which we identify with the PG, looks like[3]

$$\Delta^*(T) = T \ln \frac{e^2 A_4 \left(1 - \frac{T}{T^*}\right)}{\sigma'(T) 16\hbar\xi_c(0)\sqrt{2\varepsilon^*_{c0}\,\mathrm{sh}\left(2\varepsilon/\varepsilon^*_{c0}\right)}}, \quad (6)$$

wherein $\sigma'(T)$ is the excess conductivity measured in the experiment.

Since T^* is determined independently based on resistive measurements, and T_c^{mf}, ε, and ξ_c (0) are defined based on FCP analysis, the only unknown parameters in Eqs. (5) and (6) are the parameter from the theory in Ref. 36 $\varepsilon^*_{c0} = (T^*_{c0}/T_c^{mf} - 1) = 1/\alpha$ and the scaling coefficient A_4. In order to find the necessary parameters, the test samples were processed in the same manner for all values of x, and this approach will be examined based on the sample with $x = 0.43$. Following Ref. 36 we will consider the dependence $\sigma'^{-1}(\varepsilon)$, in order to determine ε_{c0} (the inset to Fig. 3). We assume that just as is the case in YBCO, the value σ'^{-1} is the inverse of the excess conductivity, and that it is exponentially dependent on ε over a certain temperature interval above T_{01}.[3,36] Consequently, the dependence of $\ln \sigma'^{-1}$ on ε should be linear in this temperature interval. It is easily visible that in the interval ε_{c01}-ε_{c02} (T_{c01}–$T_{c02} = (72.2$–$100.2)$ K), denoted by $\ln \varepsilon_{c01} - \ln \varepsilon_{c02}$ in Fig. 3, $\ln \sigma'^{-1}(\varepsilon)$ is

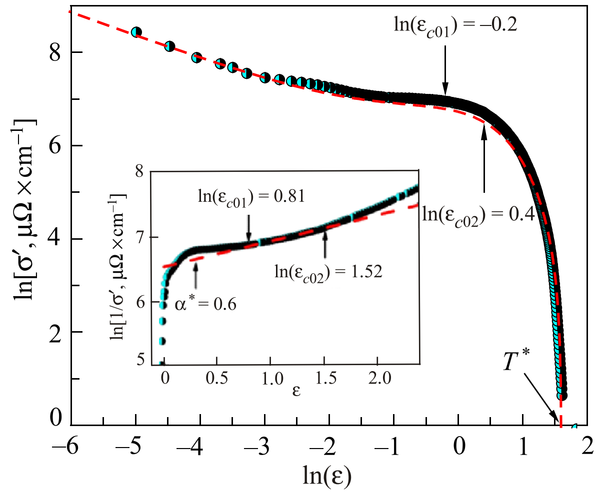

Fig. 3. The dependence of ln σ' on ln ε (◑) for the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal with $x = 0.43$ in the temperature range from T^* to T_c^{mf}. The dotted curve shows the calculation according to Eq. (5) with the parameters given in the text; ln ε_{c01} and ln ε_{c02} limit the interval of the exponential dependence $\sigma'^{-1}(\varepsilon)$. The inset shows: the dependence of ln $(1/\sigma')$ on ε (◑), dotted is the straight line, the inverse slope $1/\alpha$ of which defines $\varepsilon^*_{c0} = 1.67$.

approximated by a linear dependence $\ln \sigma'^{-1} = \ln \sigma'^{-1} + \alpha\varepsilon$ (dotted line).

As we already know[3,36] the inverse of the slope α of this linear dependence is exactly what determines $\varepsilon^*_{c0} = 1/\alpha = 1.67$ (Table 2). We can see from this table that as the value of x increases the value ε^*_{c0} also increases from 0.14 ($x = 0$) to 1.67 ($x = 0.43$). This same increase in ε^*_{c0} was also observed by us when the number of PrBCO layers in the superlattices and heterostructures YBCO-PrBCO was increased,[12] and is most likely caused by the increase in the influence of magnetism that occurs with an increasing concentration of Pr.[6]

In order to determine the A_4 coefficient we construct an experimental curve [Fig. 3(○)] over the entire temperature range from $T^* = (236 \pm 2)$ K to $T_c^{mf} = 39.67$ K and approximate it with Eq. (5).[3,9,12] The calculated curve (dashed curve in Fig. 3) is constructed from Eq. (5) with the experimentally-determined parameters $T^* = 236$ K, $T_c^{mf} = 39.67$ K, $\varepsilon^*_{c0} = 1.67$, $\xi_c(0) = 2.24$ Å and $A_4 = 14$. The alignment occurs in the region of 3D AL fluctuations, where ln σ' versus ln ε is a straight line with a slope of $\lambda = -1/2$.[3,12,27] It can be seen that Eq. (5) proposed by us (curve 1) provides a good description of the experimental dependence σ' (ε) which justifies using the coefficient A_4 and other parameters to calculate the PG according to Eq. (6).

Let us emphasize that in order to construct the dotted curve on Fig. 3, in addition to the above parameters it is also necessary to know the value of $\Delta^*(T_c^{mf}) \approx \Delta^*(T_c) = \Delta$ (Ref. 37) which is also substituted into Eq. (5) when finding A_4. In order to determine $\Delta^*(T_c)$ it is necessary to convert the experimental data into ln σ' versus $1/T$ coordinates (Fig. 4, ◑), and compare ln $\sigma'(1/T)$ with the theory using Eq. (5) (Fig. 4, solid curves).[3] The best result is obtained when the BEC ratio $D^* = 2\Delta^*(T_c)/k_BT_c = 5$ (curve 1), which corresponds to the strong coupling limit and is characteristic of YBCO.[1,3,7] Theoretical curves 2 and 3, for which $2\Delta^*(T_c)/k_BT_c = 3$ and $2\Delta^*(T_c)/k_BT_c = 7$, respectively, are also shown on Fig. 4. It can be seen that in this case the curves calculated

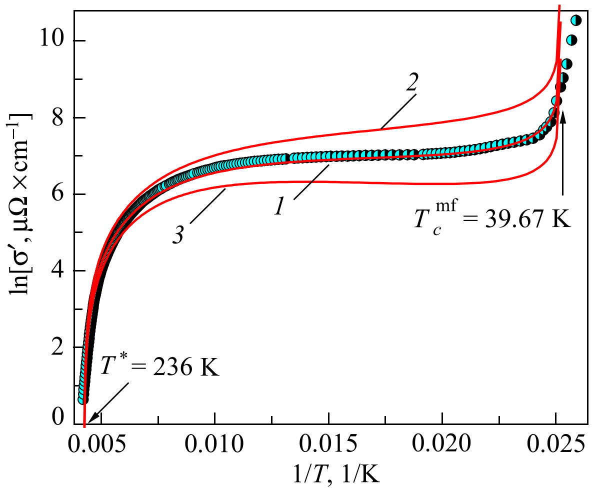

Fig. 4. The dependence ln σ' versus $1/T$ for the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal in the T^* to T_c^{mf} temperature range, at $x = 0.43$ ◑. The solid curve 1 is defined by Eq. (5) for $D^* = 2\Delta^*(T_c)/k_BT_c = 5$. Solid curves 2 and 3 are obtained for $D^* = 3$ and $D^* = 7$ and are shown for comparison.

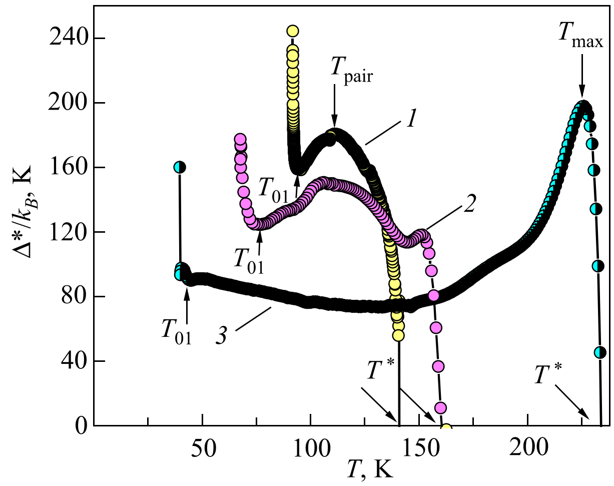

Fig. 5. The dependences Δ^*/k_B on T for the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal, calculated based on Eq. (6), for $x = 0$ (1), $x = 0.23$, and $x = 0.43$ (3).

from Eq. (5) do not correspond to the experiment. The corresponding parameters obtained in a similar manner for the rest of the samples are given in Tables 1 and 2.

The dependences $\Delta^*(T)$ obtained from Eq. (6) for $x = 0$ (curve 1), $x = 0.23$ (2) and $x = 0.43$ (3) with the set of parameters corresponding to each sample that were also used in analysis with Eq. (5), are shown in Fig. 5. At $x = 0$, $\Delta^*(T)$ increases sharply in the $T^* > T > T_{pair}$ region, demonstrating a maximum at $T_{pair} \approx 110$ K (curve 1). It is also important to note the clearly expressed minimum at T_{01}, denoted by arrows on Fig. 5. This means that in the region of SC fluctuations below T_{01} $\Delta^*(T)$ is always increasing. Such a dependence is typical for high-quality thin YBCO films with different concentrations of oxygen[3] and optimally doped YBCO single crystals.[27] T_{pair} corresponds to the BEC-BCS transition temperature, at which the local pairs are transformed into FCPs.[1–3,31,38,39] Figure 5 also shows the dependences $\Delta^*(T)$ for samples with $x = 0.23$ (curve 2) and $x = 0.43$ (curve 3). It can be seen that just as in compounds YBCO-PrBCO,[12] in this case doping with praseodymium leads to a decrease in T_c, whereas T^* increases. At the same time the maximum at T_{pair} is blurred, $\Delta^*(T_{pair})$ decreases, and eventually, the maximum at T_{pair} disappears. However, even at $x = 0.23$ there is a maximum at higher temperatures, the magnitude of which increases rapidly with increasing x. At $x = 0.43$ there is a pronounced maximum at $T_{max} \approx 226$ K, below which is a linear section with a positive slope (Fig. 5, curve 3). This type of dependence is similar to the analogous dependence $\Delta^*(T_{pair})$ that is observable in iron-containing superconductors (pnictides).[12,35]

In order to confirm this, there is a comparison of the $\Delta^*(T)$ dependence obtained for $Y_{0.57}Pr_{0.43}Ba_2Cu_3O_{7-\delta}$ in this study, against the results of the PG analysis for pnictides $SmFeAsO_{0.85}$ (Ref. 3) and $EuFeAsO_{1-x}F_x$ (Ref. 35) on Fig. 6. It can be seen that the slope of the linear section and its length, determined by the T_S and T_{SDW} temperatures, are practically the same for all samples. This result confirms the magnetic nature of the maximum that appears in the nonmagnetic YBCO upon doping with Pr. Thus, it can be argued with a high degree of certainty that the evolution of the $\Delta^*(T)$ dependence that has been discovered by us in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ and is observable with increasing x, is caused by the enhancement of the magnetic interaction in the single crystal. This conclusion seems reasonable given the fact that it has already been noted that Pr has its own magnetic moment $\mu_{Pr} \approx 3.58\ \mu_B$.[13,14]

In pnictides, T_S is the temperature of the structural transition from the tetragonal to the orthorhombic phase. T_{SDW} is the temperature that corresponds to the antiferromagnetic ordering of the iron spins and to the transition to the spin-density-wave (SDW) mode.[17,35] Thus, it can be assumed that upon doping with Pr, YBCO becomes a magnetic superconductor, in which, upon the attainment of a certain concentration of Pr, there are both structural (at T_S), and antiferromagnetic (at T_{SDW}) transitions. We note that a similar change to the temperature dependence of the PG with the appearance of the "magnetic" maximum at high T is observed by us with an increase in the number of PrBCO layers in the superlattices and heterostructures YBCO-PrBCO.[12] Consequently, the obtained result allows us to make the conclusion that the interaction between the local pairs and the magnetism (magnetic fluctuations) is of the same nature for all HTSCs in which the coexistence of superconductivity and magnetism is observed. The specific

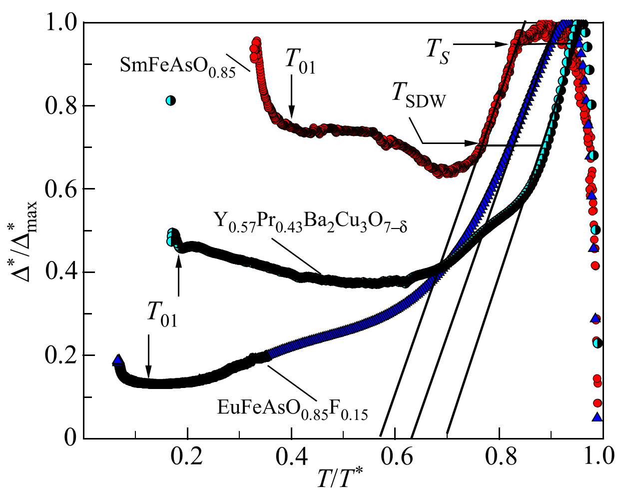

Fig. 6. $\Delta^*(T)/\Delta_{max}$ as a function of T/T^* for the $Y_{0.57}Pr_{0.43}Ba_2Cu_3O_{7-\delta}$ single crystal and iron-containing superconductors $SmFeAsO_{0.85}$ (Ref. 3) and $EuFeAsO_{1-x}F_x$.[35] The length of the linear portion between the temperatures T_s and T_{SDW} and its slope are practically the same for these samples.

mechanisms of quasiparticle scattering, caused by the presence of structural and kinematic anisotropy in the system,[40–42] could play a certain role in this process.

It should also be noted that the dependence $\Delta^*(T)$ exhibits the same behavior (Fig. 6) both for Pr doping of YBCO, and iron-containing HTSCs in the region of SC fluctuations below T_{01}. This behavior is illustrated in detail in Fig. 7, which shows the dependences $\Delta^*(T)$ for $x=0$ (curve 1) and $x=0.43$ (curve 2) near T_c. As T decreases there is a minimum that is always observed at T_{01}, after which there is a rather sharp increase in $\Delta^*(T)$, then a maximum between T_0 and T_G, and then a minimum at T_G. After T_G there is an abrupt growth of $\Delta^*(T)$, which corresponds to the HTSC transition into the critical fluctuation range at $T \leq T_c^{\mathrm{mf}}$.[12,27,43] The $\Delta^*(T)$ oscillations between T_0 and T_G, observable at $x=0$ are most likely manifestations of the specific behavior belonging to the given sample. No oscillations were observed for a similar YBCO single crystal at $T_c=91.1$ in the indicated temperature range.[27] Thus, it can be concluded that in the region of SC fluctuations before the resistive transition, all HTSCs demonstrate the same behavior, regardless of whether or not magnetic ions are present in the sample.

4. Conclusion

Detailed measurements of the resistivity $\rho(T)$ of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal with increasing praseodymium content x from $x=0$ to $x=0.43$ are conducted. It is shown that an increase in x leads to a significant increase in $\rho(T)$ and the pseudogap opening temperature T^*, as well as to a sharp decrease in T_c. For the first time the temperature dependences of excess conductivity $\sigma'(T)$ and PG, extracted from resistive measurements using the local pair model[3] were analyzed for the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal with different contents of Pr. It is shown that regardless of doping, excess conductivity $\sigma'(T)$ in the $T_c<T<T_{01}$ range is well-described by fluctuation theories: the 3D Aslamazov-Larkin theory (2) and the 2D Hikami-Larkin model (MT contribution) (3). This region of fluctuation conductivity, or SC fluctuations, is defined by the temperature T_{01} where the fluctuation Cooper pairs behave largely like superconducting pairs, but without long-range order.[28,31,32] An increase in the content of Pr leads to a marked increase in the region of SC fluctuations and to a simultaneous more-than-six-fold increase in the coherence length $\xi_c(0)$ (Table 1). Thus, as is the case in classical superconductors, the coherence length increases with decreasing T_c.

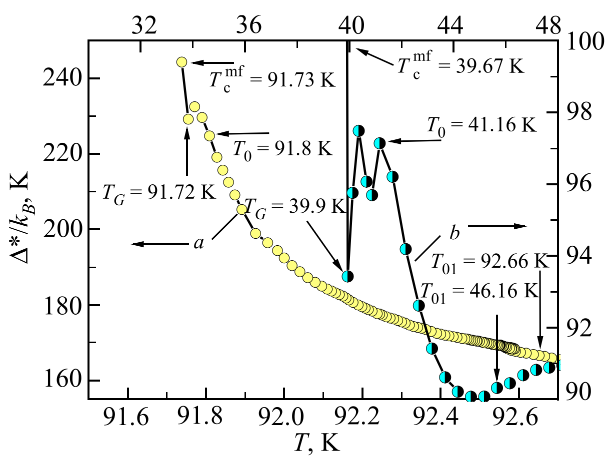

Fig. 7. The pseudogap Δ^*/k_B in the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ single crystal, constructed as a function of the temperature for $x=0$ (1) and $x=0.43$ (2) near to T_c. The top and right scales correspond to $x=0.43$.

At $x=0$ the PG temperature dependence $\Delta^*(T)$ turned out to be similar to the analogous dependence that is observed for optimally doped YBCO, with a maximum in the $T_{\mathrm{pair}} \approx 110$ K region (Fig. 5). As x increases the value of PG decreases, and the maximum at T_{pair} gradually disappears. At the same time, at $x>0.2$, along the $\Delta^*(T)$ dependence there is a maximum at higher temperatures, which is clearly expressed at $x=0.43$ and followed by a linear region with a positive slope, characterized by the temperatures T_S and T_{SDW}. (In iron-containing HTSCs, T is the temperature for the transition from the tetragonal to the orthorhombic phase, and T_{SDW} is the temperature of antiferromagnetic ordering and the transition to the spin-density-wave (SDW) mode[12,17,35]). A comparison of the dependence $\Delta^*(T)$ obtained at $x=0.43$ to the results of PG analysis for pnictides $SmFeAsO_{0.85}$ (Ref. 3) and $EuFeAsO_{1-x}F_x$ (Ref. 35) shows that the slope of the linear section and its length, determined by the T_S and T_{SDW} temperatures, are practically the same for all samples. This result points to the magnetic nature of the maximum that manifests itself in the non-magnetic YBCO upon doping with Pr. As such, it can be argued with a high degree of certainty that the observed changes in the ln σ' (ln ε) dependences and the evolution of $\Delta^*(T)$ in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ that are observable with increasing concentration of Pr, are caused by the enhancement of the magnetic interaction in the single crystal. The obtained results are confirmed by our conclusion from Ref. 12, which states that the nature of the mutual influence mechanism between superconducting and magnetic fluctuations in the temperature interval between T^* to T_c is most likely identical for all magnetic superconductors.

It is shown that the transition to the SC state, regardless of the presence or absence of magnetism, always takes place according to the same law (Fig. 7). All $\Delta^*(T)$ curves demonstrate a sharp increase in the PG with a maximum between T_0 and T_G, below T_{01}. Then there is a minimum at T_G and a sharp increase in $\Delta^*(T)$ at $T \leq T_c^{\mathrm{mf}}$, which corresponds to a transition to the critical fluctuation region. We detected such behavior of $\Delta^*(T)$ for all HTSCs, without exception.[30] Since doping with Pr does not lead to changes in the amount of oxygen in the sample, all of the observed effects can be presumably attributed to an increase in the influence of magnetism in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ with increasing Pr content.

[a]Email: solovjov@ilt.kharkov.ua

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