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Discrete Nature of Superconducting Nanochannels in the Cuprate Pseudogap Regime at $T > 200$ K

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Abstract—Intensification of segregation processes with a decrease in the charge carrier concentration in cuprates should lead, according to the string model, to a decrease the discrete width w_η of dominant bosonic stripes and an increase in their critical temperature T_c up to 1200 K. A comparison of the simulated results with the experimental data gives grounds to conclude that the anomalies of the electronic properties observed in the pseudogap regime of lightly dopes cuprates are most likely to be due to the formation of a metastable network of superconducting nanochannels with $T_c > 200$ K from the bosonic stripes limited by $w_\eta \leq 2$ nm.

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Currently it is considered as almost proved that the spatially inhomogeneous distribution of charge carriers in cuprates and some other transition metal oxides (TMO) does not indicate drawbacks of their synthesis methods. It most likely a manifestation of some deep correlations inherent to these compounds. To find out the genesis and nature of the fundamental interactions capable to initiate segregation with a tendency to quasi-one-dimensional structurization of charge and spin degrees of freedom, is one of the most topical problems in physics of condensed matter [1, 2]. In spite of the unprecedented attempts to solve it, there is no consensus in searching for adequate approaches to the interpretation of the strong spatial modulation of local electronic properties in the pseudogap regime [3, 4], which is characterized by partial suppression of the electron state density in the low-frequency ($\hbar\omega <$ 0.2 eV) regions of the spectral curves. On the basis of the experimental data obtained mainly by studying the superconducting cuprates with hole conductivity, it was established that the decrease in their doping level $\bar{n}_p$ is accompanied by a manyfold broadening of the temperature range $T \leq T^*$ in which this suppression manifests itself. $\bar{n}_p$ is the average hole concentration per unit cell of the oxygen sublattice of CuO_2 layers. The upper limit $T^*(\bar{n}_p)$ of the range under consideration is usually treated as the initial stage of pseudogap formation.

In the pseudogap regime, cuprates and structurally related TMO show an extremely rich picture of electronic properties, whose behavior is frequently far from conventional. The researchers continue to disagree in their attempts to explain the pseudogap anomalies, especially when answering the question if the charge carrier segregation is of any relevance to the pseudogap formation and the more so to high-temperature superconductivity (HTSC). Moreover, it is stated more and more persistently in recent publications that the key to understanding the nature of HTSC implemented inside a protectorate limited by a dome-shaped $T_c(\bar{n}_p)$ border with the top close to the so-called optimum value $\bar{n}_{po} = 0.16$ is in the genesis of the pseudogap anomalies [3, 5], whose temperature range of manifestation reaches 700–800 K in $La_{2-x}Sr_xCuO_4$.

For convenience, two main categories could be arbitrarily selected in the enumerous list of scenarios intended to clarify (even partially) the very contradictory situation with the genesis of pseudogap anomalies. The basic distinction between these categories is the character of the interrelations between HTSC and spontaneous implementations of short-range correlations dominant in the pseudogap regime. In addition to antiferromagnetic fluctuations and modulated waves of charge and/or spin density, they can act as composite bosons, stripes or exotic polymorphic textures with the quasi-independent ordering of charge and spin degrees of freedom up to complete splitting of the collective hole excitations into holons and spinons.

In the category of scenarios opposed to HTSC, the intrigue is built on the competition of various modifications of locally ordered charge and spin degrees of freedom. Their mission is not restricted to only expansion of their influence to the vast pseudogap sector but means primarily severe confrontation with any manifestations of the superconducting pairing, including sporadic attempts of the superconducting order parameter (SOP) to get out of the limits of its protectorate.

The majority of adepts of the opposite approach are, on the contrary, convinced that the local hole aggregates existing in the pseudogap regime must assist the SOP expansion. Some of them, demonstrating loyalty to HTSC, prefer to consider the sector between the $T_c(\overline{n}_p)$ and $T^*(\overline{n}_p)$ borders as a kind of a ground for testing every possible correlation mechanism intended to affect separate fractions of the hole community so as to activate superconducting pairing in them. It should be noted that at the initial stage of constructing such mechanisms their developers either restricted themselves to consideration of the least studied aspects of SOP fluctuation manifestations with an emphasis on its two-dimensional character or tried to find out the nature of the mysterious forces providing so strong coupling in the hole (preformed) pairs that their most heroic representatives are able to resist forward swoops of overheated phonons called to guard the high-temperature region of the $T^*(\overline{n}_p) \sim 700$ K border.

The recent experimental data [6, 7] not only increased the rating of the pseudogap state scenarios loyal to HTSC but also stimulated their authors to advance in this direction taking into account the spatially inhomogeneous hole distribution at $T < T^*(\overline{n}_p)$ in the samples of underdoped ($\overline{n}_p < \overline{n}_{po}$) cuprates [8–10]. According to the approaches [8–10], the self-organization of the hole community in a sample with $\overline{n}_p < \overline{n}_{po}$, cooled from $T^*(\overline{n}_p)$, should include several stages. The first stage is characterized by appearance of local hole pairs (composite bosons or cuperons) dispersed over CuO_2 layers. The subsequent decrease in temperature should increase the population of bosons with their simultaneous concentration in the form of growing aggregates. Further, one should expect that simultaneously with the spontaneous growth and formation of new boson aggregates, the boson isolation from the surrounding fermion-like hole excitations is activated. As a result, at this stage a large part of CuO_2 layers are weakly coupled by quantum protectorates. In these protectorates, the transition of the boson condensate into the phase-coherent state will occur at the different local critical temperatures T_{ci}, overlapping the interval from $T^*(\overline{n}_p)$ to $T_c(\overline{n}_p)$. At the final stage, the possibility of coherent boson tunneling over separate trajectories penetrating the whole sample or at least the interval between potential contacts is considered as a criterion for implementing percolation superconductivity at $T \to T_c(\overline{n}_p)$.

It should be noted that although the patch-work portrait of the pseudogap state proposed in [8–10] reflects to a great extent the recent state of the art in probing the local electron state density in CuO_2 layers, it does not contain anything radically new in comparison with the conclusion about the most likely reasons for "sagging" of the temperature dependences of the electric resistance $\rho(T)$ and the magnetic susceptibility $\chi(T)$ during cooling of the superconducting cuprates with $\overline{n}_p < \overline{n}_{po}$ below $T^*(\overline{n}_p)$, given in much more early publications [11, 12]. Based on the analysis of the investigations performed, the authors of [11, 12] showed that the deviation of the $\rho(T)$ and $\chi(T)$ curves from the high-temperature behavior due to the increasing contribution of the paramagnetic conductivity and excess diamagnetism, respectively, below $T^*(\overline{n}_p)$ is so large that cannot be explained by thermodynamic fluctuations. Thus, it is necessary to admit that the samples contain superconducting inclusions with a wide distribution function of local critical temperatures T_{ci} up to $T^*(\overline{n}_p)$. In the context of the data obtained it was predicted that the temperature $T_c(\overline{n}_p)$ of the percolation superconducting transition in perovskite-type oxides can be increased up to 160 K [11, 12]. This prediction was confirmed in 1993 by studying the properties of $HgBa_2Ca_2Cu_3O_{8+\delta}$ [13].

One can see from the $\rho(T)$ and $\chi(T)$ curves reported for $La_{2-x}Sr_xCuO_4$ samples with $x = 0.04$ [14] that their deviation from the high-temperature behavior (close to linear) begins approximately at the same temperature $T \approx 700$ K corresponding to the top limit $T^*(\overline{n}_p)$ of the pseudogap sector [15]. According to the conclusion of [11, 12], such behavior of the curves can be considered as an indication of the possibility of superconducting pairing at unlikely high temperatures. To answer the question about realizability in principle of superconducting correlations near $T^*(\overline{n}_p) \sim 700$ K, the evolution of the electronic properties of cuprates and niobates with an increase in their $\overline{n}_p$ level was studied comparatively [16]. The choice of $Ln$$Ba_2Cu_3O_{6+\delta}$ compounds (Ln = La, Nd, Gd, Dy, Tm, Lu) for such experiments was motivated not only by the possibility of reversible variation of $\overline{n}_p$ but also by the reasonable considerations, according to which at an incomplete removal of oxygen from the basic plane the remaining fragments of chains could facilitate conservation of the centers of localized superconductivity with increased coupling energy in pairs.

In fact, the analysis of the data obtained showed that the effective localization radius of hole excitations tends to the lattice period $a \approx 0.38$ nm with a decrease in $\overline{n}_p$ [16]. The estimate $T^* \sim \hbar^2/2k_B m_e d_B^2 \sim 800$ K [16] for the thermal stability of the boson condensate in the extended valleys ($2a$ wide and no less than 0.3 eV deep) of the extra potential $\tilde{U}'_{ex}(\mathbf{r})$, which are formed by the fragments of basic oxygen chains, is in agreement with the maximal value $T^*(\overline{n}_p)$ for the $La_{2-x}Sr_xCuO_4$ samples with $x = 0.38$. In the above estimate, k_B is the Boltzmann constant, m_e is the electron rest mass, and $d_B \sim 2a$ is determined by the minimal interval between bosons. Smoothing $\tilde{U}'_{ex}(\mathbf{r})$ in $YBa_2Cu_3O_{6+\delta}$ at $\delta \to 1$ should lead to the ninefold decrease in $T^* \sim \hbar^2/2k_B m_e d_B^2$ from 800 K to about 90 K as a result of the increase in d_B from $2a$ to $6a$. This calculation is in agreement with the maximal value $T_c(\bar{n}_p)$ for this cuprate. Let us remind that the problem of ordering of charge carriers in the form of superconducting strings (filamentary superconductivity) has attracted attention even at the early stage of discussion of the cuprate properties [17].

The further development of the idea of quasi-one-dimensional ordering of bosons in the form of stripes with discrete widths $w_\eta = \eta a$ resulted in the development of the string model of the pseudogap regime [5, 18–21], where η denotes the rank of bosonic stripes (BSs). The formula $T^*_{c\eta} = C^*_\eta D^*_\eta \hbar\bar{\omega}_0/[2k_B(2\eta^2 + \eta)]$ obtained within the string formalism, which characterizes the change in the temperature of stability of BSs, depending on their rank η, was soon confirmed experimentally by studying $YBa_2Cu_3O_{6+\delta}$ samples with $\delta < 0.3$. In particular, the predicted giant peaks in the vicinity of 1200 K were observed in the temperature dependences $\rho(T)$ for these samples [20, 22]. Here, C^*_η is the compatibility factor for the corrugation parameters of the extra-relief $\tilde{U}'_{ex}(\mathbf{r})$ and the transverse sizes w_η of the dominating stripes of given rank; the parameter $D^*_\eta = (1 - (1 - \delta/\delta^*_\eta)^2$ characterizes the decrease in the stability of BSs of rank η at a deviation of the basic oxygen concentration in $YBa_2Cu_3O_{6+\delta}$ from the optimum value δ^*_η, and $\hbar\bar{\omega}_0 \approx 2.05$ eV is the energy of string zero vibrations, which determines the position of the fundamental absorption band edge. The simulation results show that at the calculated value $\delta^*_\eta = 1/8+6/8^2 \approx 0.22$ the narrowest BS-II ($\eta = 2$) can resist heating up to 1200 K. The measurements showed that at the deviation from $\delta^*_\eta \approx 0.22$ the gigantic maxima in the $\rho(T)$ curves indeed shift to lower temperatures. The calculated spectral characteristics of $YBa_2Cu_3O_{6+\delta}$ for δ from 0 to 1 including the superconducting gap anisotropy, were in good agreement with the experimental data [23] as well.

Since the formula for $T^*_{c\eta}$ was derived taking into account mainly the quasi-one-dimensional correlations in the oxygen lattice, it should be applicable in principle to not only $YBa_2Cu_3O_{6+\delta}$ but also to other oxides in which the abnormal manifestations of their properties can also be caused by the formation of stripes. In this case, their maximal thermal stability at $C^*_\eta \to 1$ and $D^*_\eta \to 1$ will be also determined by the following discrete series: $T^*_{c\eta} \approx 1200$, 570, 330, 220, and 155 K for BS-II, BS-III, BS-IV, BS-V, and BS-VI respectively. It is likely that the origin of the wide maximum at ≈570 K and the inflection at ≈220 K, observed in the $\chi(T)$ curves of CuO tenorite [24], are due to the ordering of the BS-III and BS-V types. In particular, the electron diffraction data indicate that there are stripes in CuO [25]. In addition, the results of measurements on CuO samples reported in [26] show that the behavior of $\chi(T)$ below ≈ 220 TK correlates with the decrease in the resistance $R(T)$ by more than ten orders of magnitude. The interpretation of the diamagnetic jump in the $\chi(T)$ curves with a minimum close to 220 K and sagging of the temperature dependences of the screening signal $U_{sc}(T)$ below this temperature is based on the assumption of appearance of a metastable superconducting impurity phase upon cooling of reduced $CuO_{1-\delta}$ samples [27]. Moreover, it was established in [27] that when a copper film is deposited on a CuO single crystal, the sagging region in the $U_{sc}(T)$ curves shifts to higher temperatures and the intensity of the $U_{sc}(T)$ signal increases. The results of the subsequent $R(T)$ measurements of CuO single crystals with copper films deposited on their natural faces showed that after electrothermal annealing the current–voltage characteristics become nonlinear, and transitions with a sharp increase in the conductivity upon cooling are observed in the $R(T)$ curves. They can be due to the formation of superconducting regions with critical temperatures much above 400 K [28, 29]. When studying current–voltage characteristics in the entire accessible temperature range, it was established that the values of the relevant critical current $I_c(T)$ decrease by 25–50% upon heating from 80 to 400 K. The linear extrapolation of the results of measuring $I_c(T)$ to the temperature axis allowed estimating the maximal critical temperature to be $T_c \sim$ 1200 K [28, 29], a value corresponding to the top stability limit $T^*_{c\eta} \approx 1200$ K for BS-II [5, 20].

Good agreement of the calculated $T^*_{c\eta}$ values with the experimentally observed features in the temperature dependences of the TMO electronic characteristics allows one to conclude that they are most likely due to the formation of a frustrated network of superconducting nanochannels composed of BSs with $w_\eta = \eta a \le 5a$, where $a \approx 0.38$ nm.

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