DYNAMICAL DIMENSION REDUCTION IN UNDERDOPED HIGH-T_c SUPERCONDUCTORS

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We discuss a supposition according to which both pseudogap (PG) and superconducting (SC) states of underdoped high-T_c superconductors (HTSC) result from the dynamical dimension reduction when HTSC behave on cooling as if their dimensionality is changed. It is shown that the transition to a PG state at the temperature T^* occurs as a dimensional crossover from the three-dimensional ($3D$) motion of charge carriers to the two-dimensional ($2D$) one. It is this two-dimensionality at $T_c < T < T^*$ that is responsible for the crucial role of Jahn—Teller (JT) distortions, which bind up holes to form delocalized JT polarons as well as localized three-spin polarons in copper-oxygen planes, thus eliminating the competition between the pairing of carriers and their localization on JT distortions. As the temperature is lowered below $T_{\rm cr} < T^*$, local "hole—JT polaron" pairs, i.e. zero-dimensional ($0D$) SC fluctuations, are generated in the CuO_2 planes. In the temperature region $T_c < T < T_{\rm cr}$, the SC transition occurs as a sequence of two crossovers with respect to the dimensionality of SC fluctuations ($0D \to 2D$ and then $2D \to 3D$). We discuss some available experimental data on the local "hole—JT polaron" pairing and some results on the dynamical dimension reduction in the PG and SC states.

Introduction

In spite of the intensive research carried out to unveil the nature of high-T_c superconductivity, the questions concerning the pairing mechanism as well as the nature and the number of charge carriers are still open. Today for the normal state of underdoped high-T_c superconductors (UD HTSC) at $T > T^*$, the two-component model of charge carriers according to which small polarons and holes are heavy and light carriers, respectively, can be accepted as a firmly established fact. The temperature T^* above denotes a transition to the PG state characterized by the stripe ordering in the CuO_2 planes. The normal state measurements of optical conductivity in UD HTSC [1—3] were the first to provide experimental evidence for the coexistence of these two carrier types. The later spin susceptibility measurements in $La_{2-x}Sr_xCuO_4$ [4] shed light on the doping dependence of each carrier type, but the character of the polaronic state (whether it is polaronic or bipolaronic) remained unclear. This question is of fundamental importance for cuprate HTSC because the successful discovery of high-T_c superconductivity resulted in fact from the search for JT small polarons in doped antiferromagnets with high dielectric constant and mobile light oxygen ions [5]. In doped HTSC, extra holes are localized on transition metal ions; as a result, their valence is changed and strong JT distortions arise. A stronger doping leads to the transition from antiferromagnetic (AF) to metallic phase with two carrier types (for example, like in WO_{3-x} [6]), and a SC state with a rather high value of T_c is in principle possible. Indeed, a surface superconductivity with $T_c =$ 90 K was recently observed in WO_3 doped with Na ions [7].

Now it has become clear that the understanding of the nature of the PG state at $T_c < T < T^*$ will provide a clue to high-T_c superconductivity. This supposition is based on the following facts: (i) the changes in the density of states start at $T \sim T^*$ and continue down to T_c; (ii) at T_c, a coherent SC state is formed with practically no effect on the density of states; (iii) there are many signatures of temperature evolution of SC fluctuations at $T_c < T < T^*$ (see references in [8]). In [8], in the framework of the Bose—Einstein condensation theory, a three-component model of the PG state is proposed according to which bipolarons constitute the third component of charge carriers.

Here we discuss the supposition according to which the PG and SC states in UD HTSC result from the dynamical dimension reduction, when they behave on cooling as if their dimensionality changes. The transition to the PG state is thereby considered as a $3D \to 2D$ crossover with respect to the motion of charge carriers. It is the two-dimensionality at $T < T^*$ that leads to the

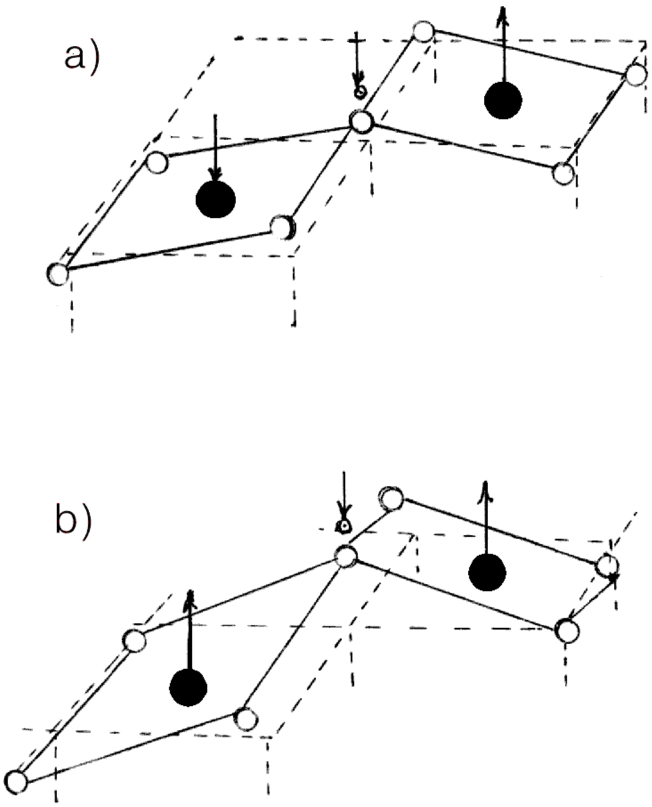

Fig. 1. The quasilocal state of a hole at $T < T^*$ (Jahn—Teller polaron, a); the local state of a hole at $T < T^*$ (three-spin polaron, b). Open circles denote oxygen ions, solid circles denote copper ions; small circles denote bound holes

crucial role of JT distortions, which bind up holes to form delocalized JT polarons and localized three-spin polarons in the CuO_2 planes. The latter polarons form chains that lead to narrow stripes with a distorted low-temperature tetragonal-like lattice in the CuO_2 planes. This actually suggests that the dimensional crossover at $T = T^*$ results in charge ordering in the CuO planes and removes the competition between the pairing of carriers and their localization on the JT distortions. At $T_{\rm cr} < T^*$, a "hole—JT polaron" pairing occurs with the formation of zero-dimensional ($0D$) SC fluctuations. In the temperature region $T_c < T < T_{\rm cr}$, there is a sequence of two crossovers: from $0D$ to $2D$ and then from $2D$ to $3D$ SC fluctuations, the latter crossover leading to a $3D$ SC transition.

1. Transition to the Pseudogap State as a $3D \rightarrow 2D$ Crossover with respect to the Motion of Charge Carriers

For UD HTSC, the charge transfer along the c axis via incoherent interlayer tunneling is due to thermal fluctuations at

$$k_{\rm B}T > t_c^2(T)/t_{ab}. \tag{1}$$

Here t_c and t_{ab} are the interlayer and intralayer hopping rates of carriers, $k_{\rm B}$ is the Boltzmann constant. At a lower temperature

$$k_{\rm B}T \simeq t_c^2(T)/t_{ab}, \tag{2}$$

thermal fluctuations are insufficient for interlayer tunneling. This leads to a $3D \rightarrow 2D$ crossover for the charge motion, when, at the temperature

$$k_{\rm B}T^* = t_c^2(T^*)/t_{ab}, \tag{3}$$

charge carriers start moving solely in the CuO_2 plane, i.e. in the $2D$ regime. This means that the transition to the PG state can be considered as a result of the dynamical dimensional reduction.

Low dimensionality enhances greatly the role of any disorder and changes the character of SC fluctuations. One of the first attempts to consider self-consistently the competition between the pairing of carriers and their localization on defects was made in [9, 10]. At $T < T^*$, the two-dimensionality in underdoped cuprate HTSC leads to the crucial role of JT distortions around two adjacent Cu^{2+} ions that bind up holes [11—14] and form quasilocal states (delocalized JT polarons) and local states (localized three-spin polarons [12], or ferrons [14]).

A mobile delocalized JT polaron is a hole residing on a complex of two adjacent $Cu^{2+} + 4O^{2-}$ "squares" with a common oxygen ion, that are distorted by JT interactions. The Q_2 normal phonon mode gives rise to oscillations of the "squares" (see Fig.1,a). The total spin of the JT polaron is $1/2$, the spins of the two Cu^{2+} ions being antiparallel. In the CuO_2 planes, these JT polarons form wide stripes with nearly undistorted orthorhombic-like lattice [15].

2. Localized Three-spin Polarons

Investigations of ferromagnetic self-trapped states of charge carriers in a doped AF crystal were initiated by Nagaev in 1968 (see references in [14]). Later, this type of states was proposed by Emery and Reiter and first observed by Kochelaev et al. who named it a

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"three-spin polaron" ([12] and references therein). The electron-paramagnetic resonance (EPR) measurements provide experimental evidence for the existence of three-spin polarons and for the presence of dynamical JT distortions with normal modes Q_4 and Q_5, which have a tetragonal symmetry and lead to an exchange spin-phonon interaction similar to the Dzyaloshinsky—Moriya interaction [16]

$$H_{s-\mathrm{ph}} = \frac{6\lambda G J^2}{a\Delta} \sum_{k,q} [\cos(ak_x) + \cos(ak_y)] \times$$

$$\times \exp(izq')[(S_k^y S_{k-q}^z - S_{-k-q}^y S_k^z) Q_{4k} +$$

$$+ (S_k^x S_{-k-q}^z - S_{k-q}^x S_k^z) Q_{5q}]. \quad (4)$$

Here J is the AF exchange constant, λ is the spin-orbit coupling constant, Δ is the average splitting between the energy levels, S_k^x is the two-dimensional Fourier transform component of the spin operator, q and q' are the projections of the three-dimensional wave vector on the CuO_2 plane and c axis, respectively, and G is the electron-phonon coupling constant. Such a small interaction cannot localize a three-spin polaron in the $3D$ system, but, for a $2D$ system at $T < T^*$, there is always a discrete level and a local state for any values of the interaction according to [11].

The isotope effect on the EPR linewidth (doubling of its value) upon the $^{16}O \rightarrow {}^{18}O$ substitution is quantitatively consistent with the exchange spin-phonon interaction in (4), and can serve as indirect evidence for the $2D$ nature of the PG state: $T^*|_{O^{16}}$=110 K and $T^*|_{O^{18}}$=180 K (see [17] and references therein). A three-spin polaron with parallel spins of two adjacent Cu^{2+} ions and a total spin of $1/2$ is a localized state of a hole bound up with two distorted $Cu^{2+} + 4O^{2-}$ "squares" with a common oxygen ion (see Fig.1,*b*). Three-spin polaron chains form narrow stripes with a distorted low temperature tetragonal-like lattice in the CuO_2 planes (D stripes [13—15]). Thus, in spite of the partial localization of carriers on the dynamical JT distortions with normal Q_4 and Q_5 modes, the competition between the pairing of carriers and their localization on JT distortions is eliminated by the charge ordering in the CuO_2 planes.

3. Possibility of "Hole—JT Polaron" Pairing

The coexistence of polarons and holes in UD HTSC at $T > T^*$ has stimulated interest in the study of possibility of their pairing. But the main problem for HTSC is the mechanism of suppression of the on-site Coulomb repulsion U_c between two particles. A possibility of such a pairing was shown in [18, 19]. The principal possibility of on-site attraction between a polaron and a hole was first shown by Kudinov in [19]: (i) polarons lead to a band narrowing and to the polaronic energy shift $E_p = g_{\mathrm{JT}}^2/2M\omega^2$ (here g_{JT} is the constant of the JT interactions between holes and mobile oxygen ions, M is the effective mass of the JT mode, ω is the frequency of oxygen ion oscillations); (ii) when $(-E_p + U_c) < 0$, both compensation of the Coulomb repulsion and on-site attraction between a hole and a polaron take place.

In [18, 19], the Zhang—Rice polarons with a zero total spin [20] were taken into account, but their pairing with holes cannot create local pairs. The Kudinov model can be easily generalized to JT polarons with a total spin of $1/2$ (see Fig.1,*a*) if, after the canonical Holstein—Lang—Firsov transformation $U = \prod_m \exp(ix_0 \sum_\sigma n_{m,\sigma} p_m)$, all the two-particle renormalized interactions (between holes, between JT polarons, and between a hole and a JT polaron) are taken into account in the Hamiltonian

$$V = \sum_{m,g,\sigma} J(g) | b_{m,\sigma}^+ b_{m+g,\sigma} + a_{m,\sigma}^+ a_{m+g,\sigma} \times$$

$$\times \exp[ix_0(p_m - p_{m+g}] + a_{m,\sigma}^+ b_{m+g,\sigma}|. \quad (5)$$

Here $J(g)$ is the non-renormalized hole interaction constant; the operators $a_{m,\sigma}^+$ and $b_{m,\sigma}^+ = a_{m,\sigma}^+ \exp(ix_0 p_m)$ create a hole and a JT polaron, respectively, on site m; x_0 and p_m are the equilibrium coordinate and moment of the oxygen ion common to the two $Cu^{2+} + 4O^{2-}$ "squares", $x_0 = g_{\mathrm{JT}}/\hbar k_{\mathrm{JT}}$, k_{JT} being the elastic constant of the JT normal mode. One can see that the JT interactions lead to different renormalization for each two-particle interaction. For $\langle \exp(ix_0 p_m) \rangle \simeq \exp(-E_p/\hbar\omega)$ [19], the generalized Kudinov's Hubbard Hamiltonian reads

$$H_H = \sum_{m,g,\sigma} (2(-E_p + U_c) n_{m,\uparrow} n_{m,\downarrow} +$$

$$+ J^*(g) a_{m,\sigma}^+ b_{m+g,\sigma}), \quad (6)$$

where $J^*(g) = J(g) \exp(-E_p/2\hbar\omega)$. All many-particle interactions are exponentially renormalized, resulting in a relatively small contribution of bipolarons to the energy with respect to the contribution of "hole—JT polaron" pairs. Kudinov showed that the pairing of a hole and a JT polaron within the BCS model can lead

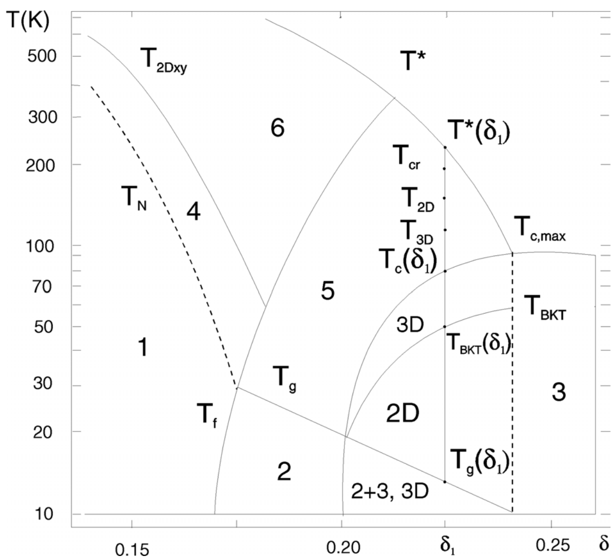

Fig. 2. Magnetic phase diagram for doped antiferromagnets. Here $T_N(\delta)$ is the doping dependence of the Neél temperature (phase *1*); $T_f(\delta)$ is the doping dependence of the ordering temperature for holes spins in the CuO_2 planes (phases *2* and *5*); $T_g(\delta)$ is the doping dependence of the temperature of the transition into the cluster spin-glass phase (phases *2* and (*2+3*)); $T_{2DXY}(\delta)$ is the doping dependence of the $2D$ XY magnetic ordering temperature for doped antiferromagnets (phase *4*); $T_{\rm BKT}(\delta)$ is the doping dependence of the BKT transition temperature for the SC state; $T^*(\delta)$ is the doping dependence of the PG transition temperature; $T_c(\delta)$ is the doping dependence of the SC transition temperature (phase *3*). The region of PG phase *5* is limited by the curves T_f, T_g, T_c, and T^*

to a SC state with a critical transition temperature $T_{\rm cr} \sim |E_p - U_c|$. In this case, a local "hole—JT polaron" pair is localized within a JT polaron complex and is characterized by the coherence length $\xi_{ab} \sim 4R_{\rm Cu-O}$ ($R_{\rm Cu-O}$ is the mean distance between Cu and O ions in the CuO_2 planes).

Thus, the dimensional crossover at $T = T^*$ results in charge ordering in the CuO_2 planes and removes the competition between the pairing of charge carriers and their localization on JT distortions. This leads to the local pairing of JT polarons and holes in the CuO_2 planes at $T_{\rm cr} < T^*$ with a distance between the local "hole—JT polaron" pairs greater than their coherence length ξ_{ab}. This implies the development of zero-dimensional ($0D$) SC fluctuations in the CuO_2 planes at $T < T_{\rm cr} < T^*$ [21—24]. Further cooling below T_c leads to an increase in the coherence length $\xi_{ab}(T)$. When at rather high values of ξ_{ab} the local pairs begin to overlap, a $0D \rightarrow 2D$ crossover for SC fluctuations occurs at $T_{2D} < T_{\rm cr}$. Then a $2D \rightarrow 3D$ crossover for SC fluctuations takes place at $T_{3D} < T_{2D}$ [25, 26].

4. The Sequence of Crossovers for SC Fluctuations

The transition to $2D$ SC fluctuations with the temperature dependence of coherence length $\xi_{ab}(T) = \xi_{ab}(T_{\rm BKT})(T/T_{\rm BKT} - 1)^{-1/2}$ leads to the semiconducting dependence of c-axis resistivity with the temperature-dependent probability of charge transfer [23, 26]:

$$t_c(T) = \frac{\xi_c^2}{\xi_{ab}^2}\left(\frac{T}{T_{\rm BKT}} - 1\right), \tag{7}$$

where $T_{\rm BKT}$ is the Berezinskii—Kosterlitz—Thouless (BKT) temperature of the $2D$ SC transition for an isolated CuO_2 plane, ξ_c and ξ_{ab} are the coherence lengths at $T = T_{\rm BKT}$. For sufficiently small $t_c(T)$, the Kats inequality $T_c/E_{\rm F} \geq t_c(T_c)$ [27] determines the temperature of the SC transition which occurs as a two-dimensional one but with a small region of $3D$ SC fluctuations (here $E_{\rm F}$ is the Fermi energy)

$$T_c \geq \frac{\xi_c^2 E_{\rm F} T_{\rm BKT}}{\xi_c^2 E_{\rm F} - \xi_{ab}^2 T_{\rm BKT}}. \tag{8}$$

For example, the analysis of the resistivity measurements on a single crystal Bi-2212 with $T_c = 80$ K [23] showed that the temperature interval width for ($0D$+$2D$) SC fluctuations was $(T_{\rm cr} - T_{3D}) \sim 120$ K and for $3D$ SC fluctuations was $(T_{3D} - T_c) \sim 10$ K (here $T_{\rm BKT} \sim 0.7T_c \sim 56$ K).

The analysis of the SC state performed in [28] showed that, at $T < 0.7T_c$, the coherence length $\xi_c(T)$ became smaller than the interlayer distance. This implies one more dynamical dimension reduction transition at which the $3D$ SC state changes into a $2D$ SC state. The lower boundary of the three-dimensional SC region can be determined as the temperature interception point of two universal temperature dependences of the ratio of squared penetration depths for a magnetic field applied along the c axis, $\lambda^2(0)/\lambda^2(T/T_c)$. One of the dependences is governed by $3D$ SC fluctuations in the BCS theory as

$$\lambda_1^2(0)/\lambda_1^2(T/T_c) = 2(1 - T/T_c), \tag{9}$$

and the other is the universal dependence for a $2D$ degenerate system:

$$\lambda_2^2(0)/\lambda_2^2(T/T_c) = \exp\frac{Te^{-1}\lambda_2^2(T/T_c)}{T_c\lambda_2^2(0)}. \tag{10}$$

The temperature interval of the "three-dimensionality" of the SC state near T_c is $\sim 0.3T_c$ in width. For example, in $La_{1.85}Sr_{0.15}CuO_4$, it is about 11 K, so the total region of the $3D$ SC and PG states is ~ 15.5 K in width [28]. The final dimensional crossover occurs at the temperature $T_g << T_{\rm BKT}$ when the $2D$ SC state of UD HTSC changes to a $3D$ cluster spin-glass SC state [29], $T_g \leq 20$ K.

Thus, the SC transition in UD HTSC is of two-dimensional character (according to the Kats definition [27]) with a limited total region of the "three-dimensionality" of the SC and PG states. The peculiarities of the normal, PG, and SC states are therefore understood by taking into account the effect of dynamical dimension reduction, when HTSC behave as if their dimensionality changes once one of the following temperatures is achieved on cooling: $T^*, T_{\rm cr}, T_{2D}, T_{3D}, T_{\rm BKT}$, and T_g (see Fig.2). As was shown above, the PG transition is a transition to the $2D$ carrier motion, and the SC transition occurs as the sequence of dimensional crossovers for SC fluctuations.

5. Discussion

Because of the dimensional crossovers for SC fluctuations, the numbers of holes (n_h) and polarons ($n_p > n_h$) [4] decrease on cooling, in agreement with the observation of a noticeable change in the density of states at $T_c < T < T^*$ [8]. For example, it was found from the Hall effect measurements in $YBa_2Cu_3O_{6+x}$ (T_c = 87.4 K) that n_h at 100 K was half that at 240 K [24]: $n_h(240K) \sim 5.4\cdot 10^{21}$ cm^{-3}; $n_h(100K) \sim 2.7\cdot 10^{21}$ cm^{-3}.

For high-T_c superconductivity, the conclusion about the decisive role of the "hole—JT polaron" pairing is in qualitative agreement with the doping dependences of each carrier type: in [4], it is shown that the T_c value ($T_c \sim n_h n_p$ for "hole—JT polaron" pairing) achieves $T_{c,\max}$ when the hole concentration is about 0.15 per Cu^{2+} ion, i.e. when the portions of polarons and holes are very close ($\sim$ 0.6 and $\sim$ 0.4, respectively). The resistivity temperature dependence is another signature of the coexistence of carriers and local "hole—JT polaron" pairs in the PG state [21, 22, 24]. The analysis of fluctuation conductivity [24] showed that the interaction between fluctuation pairs and carriers is weak, and the contributions of $0D$, $2D$, and $3D$ SC fluctuations to conductivity can be identified.

The optical conductivity measurements [30] provided the convincing evidence for the "hole—JT polaron" pairing, having shown the doubling of the c-axis component of the electronic kinetic energy and carrier

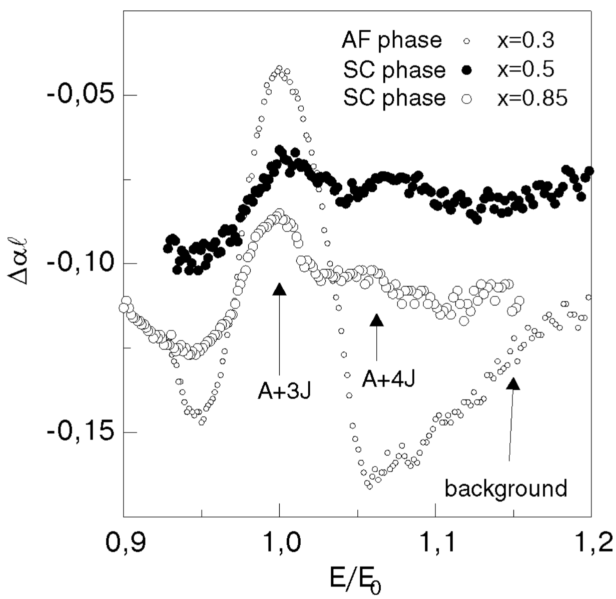

Fig.3. Bimagnon-assisted absorption band (E_0 = 2.15 eV) for an AF dielectric $YBa_2Cu_3O_{6+x}$ film (x=0.3), and for two metallic $YBa_2Cu_3O_{6+x}$ films (x=0.5 and x=0.85). In the dielectric case, the band is a single peak centered at 2.15 eV. In the metallic case, it has a doublet structure with the maxima at 2.25 and 2.28 eV. This structure appears in the PG state and becomes more prominent in the SC state

mass at $T < T^*$. Another conclusive proof of the coexistence of holes, polarons and local "hole—JT polaron" pairs in the PG and SC states is the observation [31] of a double bimagnon-assisted absorption band with the maxima at 2.15 and 2.28 eV in two metallic $YBa_2Cu_3O_{6+x}$ films (x=0.5 and x=0.85) (see Fig.3). The first component peaked at $\omega \approx \Delta_{\rm CT}+3J$ is identical with that observed in the doped AF YBCO film with x=0.3 and arises from the interband transition of a polaron accompanied by absorption of a bimagnon (two coupled magnons). Here $J \sim$0.13 eV is the exchange energy, $\Delta_{\rm CT}$ is the transfer energy. As one can see from Fig.3, the doublet structure of the band appears in the PG state and becomes more pronounced in the SC state.

In metallic YBCO samples, the $A + 3J$ component at $\omega \approx \Delta_{\rm CT} + 3J$ is absent at $T > T^*$. The observation of this component together with the $A + 4J$ component at $\omega \approx \Delta_{\rm CT} + 4J$ (see Fig.3) is the undoubted evidence of a local AF order in the PG and SC states [31]. As was shown above, JT polarons are, in fact, both charge carriers and carriers of the local AF order. We suppose that this doublet arises from the fulfilment of the "triple resonance" conditions for bimagnon absorption, similar to those for two-magnon Raman scattering in undoped AF YBCO [32, 33]. A JT polaron absorbs a photon (of energy ω) and transits into the valence band. Two charge transfers each of the energy t (between the Cu^{2+} and oxygen ions within a JT polaron complex in both directions) are accompanied by radiation of two magnons with frequencies Ω_q and Ω_{-q} if the following resonance condition is satisfied:

$$\omega \approx \Delta_{\rm CT} + 2t + \Omega_q + \Omega_{-q}. \qquad (11)$$

This condition is not satisfied for UD HTSC at $T > T^*$. If one takes into account the interactions between holes and polarons, the two-magnon absorption can lead only to an essential asymmetry with a wide right wing of the single bimagnon-assisted band: in $YBa_2Cu_3O_{6+0.1}$, it spreads up to $\omega \sim 3$ eV [30]-[33]. At $T < T_{\rm cr}$, holes and some part of the JT polarons ($n_p^* \sim n_h$) are paired; for the unpaired part of the JT polarons ($n_p - n_p^*$), the resonance condition (11) is satisfied in both PG and SC states.

The observation of the double bimagnon-assisted band is indicative of: (i) existence of JT polarons in the PG and SC states and (ii) essential charge heterogeneity of the SC state (which is the same as for the PG state). This doublet structure can also be treated as an indirect evidence for the d-wave symmetry of the SC order parameter in UD HTSC, when, below T_c, some of the unpaired polarons ($n_p - n_p^*$) percolate into the SC state along the wave vector direction with a zero order parameter.

Conclusions

To make verification of various high-T_c superconductivity scenarios, it is very important to answer the question whether the PG state in the temperature region $T_c < T < T_{\rm cr}$ is precursory of the SC state or not. The main problem in answering the question is connected with the non-three-dimensional character of SC fluctuations for that part of the fluctuation interval $T_{\rm cr} - T_{3D}$, where the pairing amplitude is already non-zero, whereas the phase rigidity is still absent. This means that, at $T > T_{3D}$, standard measurements which are dependent on phase rigidity (such as the Andreev reflection or measurements with insufficiently high magnetic fields) cannot be sensitive to SC fluctuations with non-zero pairing amplitude and without phase rigidity. The question under consideration can be answered, for example, by carrying out investigations of SC fluctuations in the region $T_{3D} < T < T_{\rm cr}$ in the presence of sufficiently high (up to 33 T) magnetic fields applied along the c axis.

The recent measurements of the pseudogap dependence on c-axis magnetic field (up to 33 T) [34] indicate that the pseudogap neither disappears nor transforms into the SC gap below T_c. This is in agreement with our conclusion according to which the PG transition at T^* occurs as a crossover from three-dimensional to two-dimensional motion of charge carriers. The existence of the pseudogap below T_c means that there are some unpaired charge carriers, JT polarons, that move solely within CuO_2 planes in the SC state. Our results suggest that the PG state and the temperature T^* should depend on magnetic field $H > H_{\rm cr}$ parallel to CuO_2 planes (here $H_{\rm cr}$ is the magnetic field sufficient enough to suppress $3D$ SC fluctuations [35]). The temperature T^* and all the dimensional crossover temperatures ($T_{\rm cr}, T_{2D}, T_{3D}$, and $T_{\rm BKT}$) should then increase.

To summarize, let us make some concluding remarks. For UD HTSC, it is shown within the two-component model of the normal state (JT polarons plus holes), that the PG and SC states result from the dynamical dimension reduction. The PG transition occurs at T^* as a dimensional crossover from three-dimensional to two-dimensional motion of charge carriers. Below $T < T^*$, it is the two-dimensionality that enhances crucially the role of Jahn—Teller distortions and causes changes in the behavior of SC fluctuations that take place when the temperature is lowered. For cuprate HTSC, the coexistence of holes and JT polarons below T^* is of fundamental importance, the role of the polarons being decisive. For strong JT interactions (e.g., ~ 1.2 eV for Cu^{2+}), the JT polarons are responsible for the polaronic shift in energy and for the compensation of on-cite Coulomb repulsion between a JT polaron and a hole in CuO_2 planes, as well as for their BCS pairing at $T = T_{\rm cr} < T^*$. As the temperature is decreased in the region $T_c < T < T_{\rm cr}$, the transition to the SC state occurs via several dimensional crossovers for SC fluctuations. A decisive answer to the question whether the PG state at $T_c < T < T_{\rm cr}$ is precursory of the SC state or not can be received by performing measurements with magnetic fields $H > H_{\rm cr}$ applied within the CuO_2 planes.

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ДИНАМІЧНА РЕДУКЦІЯ ВИМІРНОСТІ В ВИСОКОТЕМПЕРАТУРНИХ НАДПРОВІДНИКАХ З НЕВЕЛИКОЮ КІЛЬКІСТЮ ДОМІШОК

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Р е з ю м е

Обговорюється припущення про те, що псевдощілинний та надпровідний стани високотемпературних надпровідників з невеликою кількістю домішок є наслідком динамічної редукції вимірності, коли надпровідник при охолодженні поводить себе так, ніби його вимірність змінюється. Встановлено, що перехід до псевдощілинного стану при температурі T^* є вимірним кросовером від тривимірного ($3D$) руху заряду до двовимірного ($2D$). При $T^* > T$ саме двовимірність робить вирішальною роль ян-теллерівських спотворень кристалічної гратки, які у мідь-кисневій площині створюють делокалізовані ян-теллерівські полярони і локалізовані триспінові полярони. Це приводить до зарядового впорядкування у мідь-кисневих площинах та усунення конкуренції між спарюванням та локалізацією носіїв заряду. При охолодженні до температури $T_{\rm cr} < T^*$ у мідь-кисневих площинах відбувається створення локальних пар дірка—ян-теллерівський полярон, тобто виникають нульвимірні ($0D$) надпровідні флуктуації. При подальшому охолодженні $T_{\rm cr} > T > T_c$ внаслідок двох кросоверів надпровідних флуктуацій від $0D$ до $2D$ та від $2D$ до $3D$ при $T = T_c$ відбувається перехід до надпровідного стану. Обговорюються деякі експериментальні підтвердження локального спарювання дірка — ян-теллерівський полярон, а також результати вивчення динамічної редукції псевдощілинного та надпровідного станів.

ДИНАМИЧЕСКАЯ РЕДУКЦИЯ РАЗМЕРНОСТИ В ВЫСОКОТЕМПЕРАТУРНЫХ СВЕРХПРОВОДНИКАХ С НЕБОЛЬШИМ КОЛИЧЕСТВОМ ПРИМЕСЕЙ

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Р е з ю м е

Обсуждается предположение о том, что псевдощелевое и сверхпроводящее состояния в высокотемпературных сверхпроводниках с небольшим количеством примесей являются результатом динамической редукции размерности, в процессе которой сверхпроводник при охлаждении ведет себя так, как-будто его размерность изменяется. Показано, что переход в псевдощелевое состояние происходит при температуре T^* как размерный кроссовер от трехмерного ($3D$) движения заряда к двумерному ($2D$). При $T^* > T$ именно двумерность приводит к определяющей роли ян-теллеровских искажений решетки, которые в медь-кислородных плоскостях образуют делокализованные ян-теллеровские поляроны и локализованные трехспиновые поляроны. Это, в свою очередь, приводит к зарядовому упорядочению в медь-кислородных плоскостях и устраняет конкуренцию между спариванием носителей и их локализацией. При понижении температуры ниже $T_{\rm cr} < T^*$ в медь-кислородных плоскостях происходит образование локальных пар дырка—ян-теллеровский полярон, т.е. нульмерных ($0D$) сверхпроводящих флуктуаций. При $T_{\rm cr} > T > T_{\rm c}$ сверхпроводящий переход происходит в результате двух кроссоверов сверхпроводящих флуктуаций: сначала от $0D$ к $2D$, и при более низких температурах — от $2D$ к $3D$. Обсуждаются некоторые экспериментальные свидетельства локального спаривания дырка — ян-теллеровский полярон и некоторые результаты изучения динамической редукции размерности псевдощелевого и сверхпроводящего состояний.