Dynamical Dimension Reduction in Underdoped High Temperature Superconductivity

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Abstract

We discuss the supposition that both the pseudogap (PG) and the superconducting (SC) states of underdoped high-$T_c$ superconductors (HTSC) result from dynamical dimension reduction when HTSC behave on cooling if their dimensionality is changed. It is shown that the transition to the PG state occurs at the temperature $T^*$ as a dimensional crossover when charge motion changes from three-dimensional (3D) to two-dimensional (2D). Namely two-dimensionality at $T^* > T > T_c$ is responsible for the crucial role of Jahn-Teller (JT) distortions which bound up with holes and form delocalized JT polarons and localized the three spin polarons in copper-oxygen planes. This leads to charge ordering in copper-oxygen planes and removes the competition between pairing of carriers and their localization on the JT distortions. As the temperature is lowered below $T_{cr} < T^*$, the local "hole-JT polaron" pairs (i.e. zero dimensional 0D SC fluctuations) are generated in CuO planes. At $T_{cr} > T > T_c$ the SC transition occurs as a sequence of two crossovers for SC fluctuations: 0D→2D crossover and then 2D→3D crossover. Some experimental evidence of the local "hole-JT polaron" pairing and some results of the study of dynamical dimension reduction in the PG and SC states are discussed.

1 Introduction

Despite of the intensive research of the nature of high temperature (HT) superconductivity the questions about the pairing mechanism and about the nature and number of carriers remain open. Today for the normal state at $T > T^*$ for underdoped (UD) high temperature superconductors (UD HTSC) the two-component model of carriers can be considered as a firmly established fact: small polarons and holes are the heavy and light carriers respectively. Here $T^*$ is the temperature of the transition to the pseudogap (PG) state in which CuO plane are in stripe state. For normal state the measurements of optical conductivity for UD HTSC [1]-[3] provided the first evidence for coexistence of these two carrier types. Later from spin susceptibility measurements for La$_{2-x}$Sr$_x$CuO$_4$ the doping dependence of the part for each carrier type was determined [4], but the character of the polaron state (it is the polaron or bipolaron) was unclear. This question for cuprate HTSC is of fundamental importance because the existence of Jahn-Teller (JT) small polarons for doped antiferromagnets (AF) with large value of dielectric constant and mobile light carriers is of interest.
oxygen ions [5] namely was the initial point for HTSC searches. Upon doping the extra holes are localized on the transition metal ions that causes the change of their valence and leads to the strong JT distortions. At the doping increase the transition of AF into metal occurs with two carrier types (for example in \(WO_3-x\) [6]), and the superconducting (SC) transition with enough high value of \(T_c\) is in principle possible. Really the surface superconductivity with \(T_c = 90 \text{K}\) recently was observed for \(WO_3\) doped by Na ions [7].

Now it is clear that understanding of the PG state nature at \(T^* > T > T_c\) will provide a clue to HT superconductivity. This supposition is based on the following facts: 1) the change of the density of states starts at \(T \sim T^*\) and continues on up to \(T_c\); 2) at \(T_c\) the coherent SC state is formed with practicably no effect on the density of states; 3) there is a lot of evidence of an evolution of the SC fluctuations at \(T^* > T > T_c\) (see Refs. in [8]). In Ref.[8] under Bose-Einstein Condensation theory the three component model of the PG state was proposed in which bipolarons were the third component of carriers.

In this paper the authors discussed a supposition that the PG and SC states in UD HTSC result from dynamical dimension reduction when HTSC behaves as if its dimensionality changes at the lowering of the temperature below \(T^*\). At that the transition to the PG state is the dimensional 3D \(\rightarrow\) 2D crossover of charge motion. At \(T < T^*\) namely two-dimensionality leads to the crucial role of JT distortions in \(CuO\) planes which bound up with holes and form delocalized JT polarons and the localized three spin polarons in \(CuO\) planes. The chains of the latter form in \(CuO\) planes a narrow stripes with distorted low temperature tetragonal-like lattice. This means that the dimensional crossover at \(T = T^*\) leads to the charge ordering in \(CuO\) planes, and removes the competition between pairing of carriers and their localization on the JT distortions. At \(T_{cr} < T^*\) the "hole-JT polaron" pairing occurs which are zero-dimensional (0D) SC fluctuations. At \(T_{cr} > T > T_c\) a sequence of two crossovers of the SC fluctuations occurs: the first is the crossover 0D \(\rightarrow\) 2D, and second is the crossover 2D \(\rightarrow\) 3D that leads to three-dimensional SC transition.

2 The transition to the pseudogap state as 3D\(\rightarrow\)2D crossover of the charges motion

For UD HTSC incoherent interlayer tunnelling the charge transfer along \(c\) axis is the result of the thermal fluctuations at

\[
k_B T > t_c^2(T)/t_{ab}.
\]  

Here \(t_c\) and \(t_{ab}\) are the interlayer hopping rates of the charges, \(k_B\) is the Boltzman constant. At the temperature decreasing

\[
k_B T \simeq t_c^2(T)/t_{ab}
\]  

thermal fluctuations limit out the interlayer tunnelling. This leads to the dimensional crossover 3D \(\rightarrow\) 2D of charges motion when at the temperature

\[
k_B T^* = t_c^2(T^*)/t_{ab}
\]  

the charges in \(CuO\) plane moves as two-dimensional ones. This means that the transition to the PG state is the result of dynamical dimensional reduction.

Lowering of dimensionality leads to the crucial role of any disorder and to the changes of character of the SC fluctuations. One in the first attempts to consider in a self-consistent way the competition between pairing of the carriers and their localization on the defects were made in works [9]-[10]. At \(T < T^*\) for underdoped cuprate HTSC two-dimensionality
leads to the crucial role of JT distortions around two adjacent \( Cu^{2+} \) ions which bound up holes [11]-[14], and form the quasilocal states (delocalized JT polarons) and local states (the localized three spin polarons [12], or ferrons [14]).

Mobile delocalized JT polaron is the quasilocal state of hole bounded up with complex of two adjacent distorted by JT interactions “squares” \( Cu^{2+} + 4O^{2−} \) with common oxygen ion, and \( Q_2 \) phonon normal mode leads to the oscillations of “squares” (see Fig. 1a). Total spin of JT polaron is equal 1/2, and spins of two \( Cu^{2+} \) ions are antiparallel. In \( CuO \) plane these JT polarons form wide \( U \) stripes with nearly undistorted low temperature orthorhombic-like lattice [15].

3 The localized three spin polarons

The studying ferromagnetic self-trapped states of a charge carriers in a doped AF crystal was began in 1968 by Nagaev (see Refs.in [14]). Later this type of states has been proposed by Emery and Reiter, and at first it was observed and named “the three spin polaron” by Kochelaev et al. ([12], and Refs. there). Electron-paramagnetic resonance (EPR) measurements provide experimental evidence of the existence of the three spin polarons and the presence of dynamical JT distortions with normal modes \( Q_4 \) and \( Q_5 \), which have tetragonal symmetry and lead to exchange spin-phonon interaction similar to the Dzyaloshinskii-Morya interaction [16]

\[
H_{s-ph} = \frac{6\lambda G J^2}{a\Delta} \sum_{k,q} [\cos(ak_x) + \cos(ak_y)] \cdot \exp(iq') \{|S^{y}_{k}S^{z}_{k - q}\} - S^{y}_{k - q}S^{z}_{k} - \{S^{x}_{k}S^{z}_{k - q} - S^{x}_{k - q}S^{z}_{k}\}Q_{4k} + \{S^{x}_{k}S^{z}_{k - q} - S^{x}_{k - q}S^{z}_{k}\}Q_{5q}.
\]

where \( J \) is the exchange antiferrogrnetic coupling constant, \( \lambda \) is spin-orbit coupling constant, \( \Delta \) is an average splitting between energy levels, \( S^{x}_{k} \) is a two dimensional Fourier’s transforms a component of the spin operator, \( q \) and \( q' \) are projections of three dimensional wave vector on the \( CuO \) plane and \( c \)-axis respectively, and \( G \) is electron-phonon coupling constant. This small interaction cannot pin the three spin polaron in 3D system but at \( T < T^{∗} \) for 2D system local state exists at any values of the interactions in the frame of I.M.Lifshits theory [11].

The isotope effect on the EPR linewidth (it doubles) upon substitution \( ^{16}O \rightarrow ^{18}O \) quantitatively adjusts with exchange spin-phonon interaction assistance in (4), and can be indirect evidence of 2D nature of the PG state: \( T^{∗}|_{O^{16}} = 110 \) K, and \( T^{∗}|_{O^{18}} = 180 \) K ([17] and Refs. there). The three spin polaron with parallel spins of two adjacent \( Cu^{2+} \) ions and with total spin 1/2 is localized state of a hole bounded up with two distorted "squares" \( Cu^{2+} + O^{2−} \) with common oxygen ion (see Fig.1b). Their chains form in \( CuO \) plane narrow stripes with distorted low temperature tetragonal-like lattice (D stripes [13]-[15]). Thus in spite of localization of the carriers part on dynamical JT distortions with normal modes \( Q_4 \) and \( Q_5 \), charge ordering in \( CuO \) plane removes the competition between pairing of carriers and their localization on the JT distortions.

4 The possibility of the JT polaron and hole pairing

For UD HTSC the coexisting at \( T > T^{∗} \) of polarons and holes stimulated the interest to the studying the possibility of their pairing, but at that the mechanism of the suppression
of on-site Coulomb repulsion $U_c$ for two particles is the main problem for HTSC. In Refs. [18]-[19] the possibility of such pairing was shown. Kudinov [19] at the first shows on the following results: (i) polarons lead to the band narrowing and to the polaron shift of the energy $E_p = g_{JT}^2/2M\omega^2$ (here $g_{JT}$ is the constant of JT interactions of holes with mobile oxygen ions, $M$ is the effective mass of JT polaron); (ii) at $-(E_p + U_c) < 0$ both as the compensation of Coulomb repulsion, and so the on-site attraction between the hole and polaron take place.

In Refs. [18]-[19] the Zhang-Rice polarons [20] were taken into account which have total spin equal zero, and their pairing with holes cannot lead to the local pairs. But Kudinov model easily generalizes for JT polarons with spin equal 1/2 (see Fig. 1a), if after canonical Holstein-Lang-Firsov transformations $U = \prod_m \exp(ix_0\sum_{m,\sigma}n_{m,\sigma}p_m)$, in Hamiltonian all two-particle renormalized interactions are taking into account (between holes, between JT polarons, as well between the hole and JT polaron):

$$V = \sum_{m,g,\sigma} J(g)[b_{m,\sigma}^+ b_{m+g,\sigma} + a_{m,\sigma}^+ a_{m+g,\sigma} \cdot \exp(ix_0(p_m - p_{m+g}) + a_{m,\sigma}^+ b_{m+g,\sigma}].$$

(5)

Here $J(g)$ is non-renormalized interaction constant between holes, $x_0 = g_{JT}/\hbar k_{JT}$, $k_{JT}$ is elastic constant of JT normal mode, operators $a_{m,\sigma}^+$, and $b_{m,\sigma}^+$ create the hole and JT polaron on site $m$, respectively, and $p_m$ and $x_0$ are the impulse and equilibrium coordinate of the common oxygen ion for two adjacent “squares” $Cu_2^{2+} + O^{2-}$. One can see that strong JT interactions lead to different renormalization of all two-particle interactions. At $<\exp(ix_0p_m) > \approx \exp(-E_p/\hbar\omega)$ [19] generalized Kudinov’s Habbarg Hamiltonian is equal

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

(6)

where $J^*(g) = J(g)\exp(-E_p/\hbar\omega)$. All many particles interactions are exponential renormalized that leads to the small contribution of bipolarons in the energy relatively with the contribution of the on-site “hole-JT polaron” pairs (because former contribution has exponential dependence on the distance between two JT polarons [19]). As it shown by Kudinov in BCS model the pairing hole and JT polaron leads to the possibility of the SC transition in $CuO$ plane with the temperature $T_{cr} \sim |E_p - U_c|$. At that the local pair “hole-JT polaron” occupies the of JT polaron complex, and has coherent length $\xi_{ab} \sim 4R_{Cu-O}$ ($R_{Cu-O}$ is the mean distance between $Cu$ and $O$ ions in $CuO$ plane).

Thus, the dimensional crossover at $T^*$ leads to the charge ordering in $CuO$ plane and removes the competition between pairing of the carriers and their localization on the JT distortions. For cuprate HTSC the coexistence at $T < T^*$ of holes and JT polarons is fundamentally important but decisive role belong to the latter. JT polarons lead to polaron shift of the energy, and to the compensation of on-site Coulomb repulsion between JT polaron and hole in $CuO$ planes. This leads at $T_{cr} < T^*$ to the local pairing of JT polarons and holes, i.e. to zero-dimensional (0D) SC fluctuations [21]-[24]. The temperature lowering leads to the increasing of the coherent length $\xi_{ab}(T)$, so that at enough big $\xi_{ab}$ local pairs begin overlap, and at $T_{2D} < T_{cr}$ the dimensional crossovers 0D→2D of the SC fluctuations occurs. Second crossover 2D→3D of the SC fluctuations occurs at $T_{3D} < T_{2D}$ [25]-[26].
5 Dynamical dimension reduction for the PG and SC states of UD HTSC

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

\[
t_c(T) = \frac{\xi_c^2}{\xi_{ab}^2} \left( \frac{T}{T_{BKT}} - 1 \right),
\]

(7)

where \( T_{BKT} \) is Berezinskii-Kosterlitz-Thouless temperature (BKT) of the 2D SC transition for the isolated CuO plane, and \( \xi_c \) and \( \xi_{ab} \) are the values of the coherent lengths at \( T = T_{BKT} \). At sufficiently small \( t_c(T) \) the Kats inequality [27] \( T_c/E_F > t_c(T_c) \) determines the temperature of the SC transition which occurs as two dimensional one with small region of the 3D SC fluctuations (here \( E_F \) is Fermi energy)

\[
T_{BKT} < T_c < T_{BKT} \left( 1 - \frac{\xi_{ab}^2 T_{BKT}}{\xi_c^2 E_F - \xi_{ab}^2 T_{BKT}} \right),
\]

(8)

For example, from the analysis of the resistivity measurements in single crystal Bi-2212 with \( T_c = 80K \) [23] it follows that the region of the \((0D+2D)\) SC fluctuations \((T_{cr} - T_{3D}) \sim 120K\), and the region of the 3D SC fluctuations \((T_{3D} - T_c) \sim 10K\), and \( T_{BKT} \sim 0.7T_c \sim 56K \).

At the analysis of the SC state in [28] it was shown that at \( T < 0.7T_c \) the coherence length \( \xi_c(T) \) becomes less than the interlayer distance. This means that once more dynamical dimension reduction occurs at which the 3D SC state changes into the 2D SC state. The boundary of the region of ”three-dimensionality” of the SC state can be determined as the temperature at which the two universal temperature dependencies of the ratio of the squares of the penetration depths of a magnetic field directed along \( c \) axis, \( \lambda^2(0)/\lambda^2(T/T_c) \), are crossing: one is determined by the 3D SC fluctuations in the BCS theory

\[
\lambda_2(0)/\lambda_2(T/T_c) = 2(1 - T/T_c)
\]

(9)

and another is universal dependence for the 2D degenerate system

\[
\lambda_2^2(0)/\lambda_2^2(T/T_c) = \exp \frac{T e^{-1} \lambda_2^2(T/T_c)}{T_c \lambda_2^2(0)}.
\]

(10)

The temperature interval of ”three-dimensionality” of the SC state occupies only two temperature regions, \( \Delta_1 = T_c - T_{BKT} \) near \( T_c \), and \( \Delta_2 = T_{BKT} - T_g \) where \( T_g \) is the temperature of the transition into spin cluster glass SC state (state (2+3) on fig.2)[29]. For example, \( \Delta_1 \sim 11K \) for \( La_{1.85}Sr_{0.15}CuO_4 \), and region of ”three-dimensionality” of the SC and PG states near \( T_c \) is equal \( T_{3D} - T_{BKT} \sim 15.5K \) [28]. For UD HTSC last dimensional reduction occurs at temperature \( T_g \sim T_{BKT} \) when the 2D SC state changes on 3D spin cluster glass SC state [29], and the values of \( T_g < 20K \).

Thus, for UD HTSC the SC transition has two-dimensional character (according to the Kats definition [27]) with limited total region of ”three-dimensionality” of the SC and PG states. The peculiarities of normal, the PG and SC states can be understood taking into account the effect of dynamical dimension reduction under cooling when HTSC behaves as if its dimensionality repeatedly changes at \( T^*, T_{cr}, T_{2D}, T_{3D}, T_{BKT}, T_g \) (Fig.2). At that
the PG transition is a transition to 2D carriers motion at $T^*$, and the SC transition occurs as a sequence of dimensional crossovers of the SC fluctuations.

6 Discussion

For UD HTSC at dimensional crossovers of the SC fluctuations holes number $n_h$ and polaron number $n_p > n_h$ [4], are decreasing that is according with the observation of the noticeably change of the density of states at $T^* > T > T_c$ [8]. For example, at the Hall effect measurements for $YBa_2Cu_3O_{6+x}(T_c = 87.4K)$ was found out that $n_h$ decreases at lowering the temperature from $240K$ up to $100K$ [24]: $n_h(240K) \sim 5.4 \cdot 10^{21} cm^{-3}$; $n_h(100K) \sim 2.7 \cdot 10^{21} cm^{-3}$.

For HT superconductivity the conclusion about the decisive role of "hole-JT polaron" pairing qualitatively comes to an agreement with the doping dependence of the part of each carriers type relatively of total carriers number: in Ref. [4] for $La_{2-x}Sr_xCuO_4$ it was shown that the value of $T_c \rightarrow T_{c,\text{max}}$ (at"hole-JT polaron" pairing $T_c \sim n_h \cdot n_p$) at the hole concentration $\sim 0.15$ ion $Cu^{2+}$ when $\frac{n_p}{n_p+n_h} \sim 0.6$ and $\frac{n_h}{n_p+n_h} \sim 0.4$.

The temperature dependence of the resistivity also evidences about the coexistence of carriers and local pairs "hole-JT polaron" in the PG state [21]- [22], [24]. The studying fluctuational in-plane conductivity [24] shown that the interactions of fluctuational pairs with the carriers are weak, and the contributions into conductivity of the 0D, 2D and 3D SC fluctuations are been identified.

The measurements of optical conductivity are the convincing evidence of "hole-JT polaron" pairing where it is shown that at $T < T^*$ the c-axis component of electronic kinetic energy and carriers mass double [30]. Once more convincing example of the coexistence of the holes, polarons a local pairs "hole-JT polaron" in the PG and SC states is the observation of a doublet structure of two-magnon absorption band with maxima at 2.15eV and 2.28eV in two metallic films $YBa_2Cu_3O_{6+x}$ (x=0.5 and x=0.85 ) (see fig.3) [31]. Its first component with energy $\omega \approx \Delta_{CT} + 3J$ is identical to that which was observed in doped AF with $x = 0.3$, and was caused by two-magnon absorption at interband transition of polaron (here $J \sim 0.13eV$ is the exchange energy, $\Delta_{CT}$ in transfer energy). It is seen that the doublet structure appears in the PG state, and becomes more prominent in the SC state.

It is known that in metal phase of the sample at $T > T^*$ this component is not observed. For metal films at $T < T^*$ the observation of this component together with second component with $\omega \approx \Delta_{CT} + 4J$ undoubtedly attest to the fact that developed antiferromagnetic fluctuations exist in the PG and SC states [31]. We conjecture that this doublet was caused by the fulfillments of the condition of the "triple resonance" for two-magnon absorption, similar to that at Raman scattering for undoped AF [32]-[33]. JT polaron absorbs of photon (with energy $\omega$) and transfer into valence band. Two transfers of the charge with energy $t$ (between $Cu^{2+}$ and oxygen ion within JT polaron complex, there and back) lead to the radiation of two magnons with the frequencies $\Omega_q$, $\Omega_{-q}$ at the resonance condition

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

For UD HTSC at $T > T^*$ this condition is not practicable with taken into account the interactions between holes and polarons, and two-magnon absorption leads only to an essential asymmetry and big width of right hand of two-magnon absorption band: for $YBa_2Cu_3O_{6+0.1}$ up to $\omega \sim 3eV$ [30]-[33]. At $T < T_c$ holes and part of JT polarons ($n_p^* \sim n_h$) are in pairing state, and for unpaired part of JT polarons $(n_p - n_p^*)$ resonance condition (11) takes place in both the PG and SC states.
The observation of the doublet structure of two-magnon absorption band evidences about (i) the existence of the JT polarons in PG and SC states, and about (ii) essential charge heterogeneity of the SC state (the same as for the PG state). The doublet structure of two-magnon absorption band for the SC state is an indirect evidence of $d$-wave symmetry of the SC order parameter for UD HTSC as well: at $T_c > T$ some part of unpaired polaron ($n_p - n_p^*$) percolates through the direction of wave vector where the order parameter is equal zero.

Recent measurements of the $c$–axis charge pseudogap dependence on the temperature and on the magnetic field $H//c$-axis [34] indicate that the pseudogap neither disappears nor continuously transforms into the SC gap below $T_c$, and this comes an agreement with our statement that the PG transition occurs at $T^*$ as the dimensional crossover from three-dimensional charges motion to the two-dimensional one. The existence of the pseudogap at $T < T_c$ means that there are a part of unpaired carriers which in the SC state moves only in $CuO$ plane, and we above see that JT polarons are these unpaired carriers.

7 Concluding remarks

For verification of various HTSC scenarios it is very important to know the right answer on the question: is the PG state at the temperature $T^* > T > T_c$ a precursor of the SC state or not. The problems of the decision of this question is connected with non-three-dimensional character of the SC fluctuations for the part of fluctuational interval $T_{cr} - T_{3D}$ where pairing amplitude is non-zero, but phase rigidity is lost. This means that at $T_{cr} > T > T_{3D}$ the standard measurements which are depending on phase rigidity (such as Andreev reflection or insufficiently high magnetic field) cannot be sensitive to the SC fluctuations with non-zero pairing amplitude, but without phase rigidity. For example, the studying of the dependence of the fluctuations at $T_{cr} > T > T_{3D}$ under sufficiently high (up to 33 T) magnetic field $H//c$-axis can give the decisive answer on this question.

Our results mean that the temperature $T^*$ will be depending on magnetic field $H > H_{cr}$ which is parallel to $CuO$ plane (here $H_{cr}$ is the magnetic field which leads to suppression of the 3D SC fluctuations [35]). At that $T^*$, and all the temperatures of dimensional crossovers of the SC fluctuations ($T_{cr}, T_{2D}, T_{3D}$, and the temperature $T_{BKT}$) receive the positive additions.

To summarize, in this paper for UD HTSC it is shown that the coexistence of holes and Jahn-Teller polarons is fundamentally important but decisive role belong to the latter. At that the pseudogap transition occurs at $T^*$ as the dimensional crossover from three-dimensional charges motion to two-dimensional. Two-dimensionality leads to the charge ordering in $CuO$ plane and removes the competition between pairing of the carriers and their localization on the Jahn-Teller distortions. At the cooling dimensionality repeatedly changes in the pseudogap and in the superconducting state. The measurements under high magnetic field which is parallel to copper-oxygen plane can give the decisive answer on the question: is the pseudogap state a precursor of the superconducting state or not.

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**Figure captions**

Fig. 1a). Quasilocal state of hole at $T < T^*$ (Jahn-Teller polaron). Fig. 1b). Local state of hole at $T < T^*$ (the three spin polaron). Light circles denote oxygen ions, dark circles denote copper ions; small circles denote bound holes.

Fig. 2. Magnetic phase diagram for doped antiferromagnets and underdoped HTSC:
- $T_N(\delta)$ is the doping dependence of Neel temperature (AF state 1);
- $T_f(\delta)$ is the doping dependence of the temperature of the ordering holes spin in CuO plane (states 2, 5);
- $T_g(\delta)$ is the doping dependence of the temperature of the transition into spin cluster glass state (states 2 and (2+3));
- $T_{2D,XY}(\delta)$ is the doping dependence of the temperature of 2D XY magnetic ordering for doped AF (state 4);
- $T_{BKT}(\delta)$ is the doping dependence of the temperature of BKT transition for the SC state;
- $T^*(\delta)$ is the doping dependence of the temperature of the transition in the PG state;
- $T_c(\delta)$ is the doping dependence of the temperature of the transition into the SC state (3). The region of the PG state (5) limited by the curves $T_f, T_g, T_c$ and $T^*$.

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