QUANTUM NATURE OF NON-FERMI CHARGE CARRIERS FOR PSEUDOGAP STATE OF HIGH-T_C SUPERCONDUCTORS

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For pseudogap state of underdoped cuprates high temperature superconductors (HTS) with stripe structure of copper-oxygen plane an approach for describing of *U*-stripe as two-dimensional state with vortex-like excitations is developed. At high temperatures these vortices are pinned by copper-oxygen complexes in *U*-stripes, and at lowering temperature the transition of pinned vortices to moving ones occurs at $T \le T_f(p)$ where *p* is doping concentration. It is shown that this transition is the result of quantum diffusion which for quantum crystals was predicted by A.F. Andreev and I.M. Lifshits (1969). Quantum diffusion leads to non-Fermi charge carriers, and to two universal lines for common phase diagram of underdoped cuprates. This consideration let us to suppose that pseudogap state of underdoped cuprates is determined only by properties of copper-oxygen plane.

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1. INTRODUCTION

Despite the 35-year history of investigations of the 2D superconductivity, this problem arises the interest of researchers, in particular, in studying the influence of a perpendicular magnetic field on the rather strongly disordered superconducting films [1-4][1], as well as, in studying the pseudogap (PG) state of underdoped (UD) quasi-2D cuprates HTS at $T < T^*(p_{sh})$ (here $T^*(p_{sh})$ is the temperature of transition to PG state, and p_{sh} is the fraction of doped holes per Cu ion in the CuO_2 plane). The photoemission spectroscopy (ARPES) shows that both the PG and the superconducting (SC) gaps are opened near the same Fermi-surface region (π,0), and the dispersion of mobile charge carriers in the quasi-2D nonconducting doped antiferromagnets (DAFs) (see review [5], Fig.18) is strongly renormalized by the antiferromagnetic (AFM) interactions in the CuO_2 plane[2]. In spite of fact that in 1990 it has been evidenced experimentally that the localized hole function contains ≈ 90% *d*-contribution of copper ions and ≈10% p_{sh}-contribution of oxygen ions, and the delocalized charge carrier function contains as much as ≈ 80% p_{sh}-contribution [6-7], only recently one obtained the convincing proof of the *d*+*ip* mixed symmetry of holes in PG state [8].

According to the Varma theory of local closed (*LC*) currents [9,10], a localized hole of a JT divalent copper ion belongs to the magnetic copper-oxygen complex $Cu^{2+}O_4^{-2}$. The known results of optical studies carried out by V.V. Eremenko and S.V. Novikov [11] showed that in the DAF charge carrier can move only within its proper magnetic sublattice. This allows suppose that in an AFM metal there are two types of charge carriers, each of which moves though its proper sublattice of magnetic complexes $Cu_{\uparrow}^{2+}O_4^{-2}$ or $Cu_{\downarrow}^{2+}O_4^{-2}$ [12].

Comparative analysis was performed recently in Refs. [13,14] for the spectra of the intra-zone optical conductivity of monocrystals $YBa_2Cu_3O_y$ ($6.75 \ge y \ge 6.35$) and $La_{2-x}Sr_xCuO_4$ ($0.01<x<0.125$) both with AFM ordering and in the SC states. It has been shown that in all samples there are general conformities clearly defined in the low-temperature region. In rather strongly UD samples the low temperature (LT) spectrum consists of two absorption bands: a coherent Drude mode that noticeably converges with decreasing temperature, and a middle infrared (mid IR) band. The frequency of mid IR band shifts with the doping from $\omega \sim 5000\ cm^{-1}$ (at y=6.28) to $\omega \sim 1300\ cm^{-1}$ (at y=6.75). It is important to note that the Drude mode, which is known as a standard characteristic of the transport in metals, is also observed in DAFs. Localization elements become noticeable only in the very weakly DAF or at sufficiently high temperatures $T \sim T^*(p_{sh})$.

Striking results presented in Refs. [13,14] contradict to the usual determination of weakly doped cuprates as "AFM insulators", and agree with the assumptions of M. Imada et al. [15,16] that with the dopant concentration growth $p_{sh} \ge p_{cr}$, or at the lowering temperature the transition of Mott insulator to the non-Fermi liquid metal at $T \le T_f(p_{sh})$ consists in the arising number $N_{mch}(T)$ of mobile charge carriers (*mch*). These carriers are compatible with antiferromagnetism of the CuO_2 plane, and $N_{mch}(T)|_{T>T_f}=0$. At lowering temperature $N_{mch}(T)|_{T<T_f}>0$, and

$$T_f(p_{cr}) = T_N(p_{cr}) = T_g(p_{cr})\,. \qquad (1)$$

Here $T_g(p_{sh})$ is line of transition of DAF into 3D state of cluster spin glass, and $T_N(p_{sh})$ is the Neel tempera-

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[1] In Ref. [3,4] it was observed that under the effect of a perpendicular magnetic field in InO and MoGe films an unusual metallic state arises named as a "vortex metal".

[2] It should be noted that the Laflin calculations on the dispersion of 2D spinon (elementary excitations with the charge equal to zero and the spin $\pm hc/2e$) are in a good agreement with the ARPES measurement results (see the references in [5]).

ture, and p_{cr} is critical point of the co-existence of these states with PG state.

The formation of *D*-stripes in $\mathrm{CuO_2}$ plane with distorted LT tetragonal structure indicates on the existence of "molecules" $\mathrm{Cu^{3+}O_4^{2-}}$: for these molecules, as for other d^8-plane square complexes[3], the tendency towards distortion of the copper-oxygen planes is inherent. The nondegenerate *A*-state of $\mathrm{Cu^{3+}}$ ion in *D*-stripes is characterized by the minimum energy

$$\varepsilon_A^D < \varepsilon_E^D \ . \tag{2}$$

An undistorted LT orthorhombic structure of *U*-stripes is close to an octahedral one, for which the energy ε_E^U of a twofold degenerate *E*-state of a Jahn-Teller $\mathrm{Cu^{2+}}$ ion is less than the energy of the non degenerate *A*-state of a $\mathrm{Cu^{3+}}$ ion:

$$\varepsilon_A^U - \varepsilon_E^U = \Delta_U , \ \ \Delta_U > 0. \tag{3}$$

Generalization of Varma model of circular closed (*CC*) currents [8] for a localized *d*-hole of $\mathrm{Cu^{3+}}$ ion in *U*-stripes [16] showed that at $T^*(p) \geq T$ vibronic interactions lead to the ordering of hole spins. This ordering are consistent with copper ion spins, and leads to the transition of a nonmagnetic "molecules" $\mathrm{Cu^{3+}O_4^{2-}}$ into the nonmagnetic complex $\mathrm{Cu_{\uparrow}^{2+}O_4^{2-}} + v_{\downarrow}$ with a circular closed current $v_{\downarrow}$ around the oxygen ions (or with $v_{\uparrow}$ on $\mathrm{Cu_{\downarrow}^{2+}O_4^{2-}}$ complex), the magnetic moment of which compensates the spin of $\mathrm{Cu_{\uparrow}^{2+}}$ (or $\mathrm{Cu_{\downarrow}^{2+}}$) ion.

So there is a certain analogy between the influence of doping on the properties of AFM copper oxides and the Abrikosov-Hofstadter problem for delocalized charge carrier in a magnetic field:

1) the influence of local magnetic fields of the four neighboring $\mathrm{Cu_{\uparrow}^{2+}}$ (or $\mathrm{Cu_{\downarrow}^{2+}}$) ions on magnetic complex $\mathrm{Cu^{2+}O_4^{2-}}$ gives rise to four Varma *LC* currents in the quadrants of the complex (see Fig. 3,a in Ref. [16]) with summary magnetic moment equal zero, and $M_{\mathrm{Cu^{2+}O_4}} \approx m_{\mathrm{Cu^{2+}}}$;

2) the influence of local magnetic fields of the four neighboring $\mathrm{Cu_{\uparrow}^{2+}}$ (or $\mathrm{Cu_{\downarrow}^{2+}}$) on the nonmagnetic "molecule"[4] $\mathrm{Cu^{3+}(\uparrow)O_4^{2-}}$ (or $\mathrm{Cu^{3+}(\downarrow)O_4^{2-}}$), leads to rise of *CC* currents with coincident direction of motion of hole in quadrants of the complex them (for example see Fig.3,b with counterclockwise motion of the hole in the quadrants). As it is seen in Fig.3,b Ref. [16] compensation of the currents along the $\mathrm{Cu^{2+} - O^{2-}}$ lines in adjacent quadrants results to two ring currents with opposite directions of holes motion. The first ring current is localized around the copper ion and is evidenced that the $\mathrm{Cu^{3+}(\uparrow)}$ ion has gone into the magnetic state $\mathrm{Cu_{\uparrow}^{2+}}$, corresponding to AFM order in $\mathrm{CuO_2}$ plane. The second ring current around the oxygen ions of the complex attests that the localized hole has undergone a transition to a vortexlike 2D state with mixed symmetry $d_{x^2-y^2} \pm i(p_x + p_y)$. These ring currents can be called a vortex $v_{\downarrow}$ on a $\mathrm{Cu_{\uparrow}^{2+}O_4^{2-}}$ complex, and antivortex $v_{\uparrow}$ on a $\mathrm{Cu_{\downarrow}^{2+}O_4^{2-}}$ complex. The condition of conservation of a magnetic moment in the nonmagnetic "molecule" defines the directions of the ring currents $m_{v\uparrow} = -m_{\mathrm{Cu_{\downarrow}^{2+}}}$ and $m_{v\downarrow} = -m_{\mathrm{Cu_{\uparrow}^{2+}}}$, and the energy of these vortices is equal ε_0

$$E_{v\uparrow} \approx E_{v\downarrow} \approx \varepsilon_0 = \varepsilon_A^U - \varepsilon_E^U = \Delta_U \ . \tag{4}$$

These ring currents in *U*-stripes at $T \leq T^*(p)$ can be considered as localized vortices $v_{\downarrow}$ or $v_{\uparrow}$ which are pinned by the magnetic complexes $\mathrm{Cu_{\uparrow}^{2+}O_4^{2-}}$ (or $\mathrm{Cu_{\downarrow}^{2+}O_4^{2-}}$). This supposition agrees with the scanning SQUID microscopy data [17] for thin LSCO films with T_c=18 K about the existence in the PG state of closed internal currents and "possible presence of pinned vortices" at $T \approx 90$K.

2. TO THE QUANTUM NATURE OF TWO-DIMENSIONAL "VORTEX METAL" STATE FOR UNDERDOPED HTS CUPRATES

The probability *w*~ 1/*t* of transition of pinned vortices *(pv)* $v_{\downarrow}$ (or $v_{\uparrow}$) from the magnetic complex $\mathrm{Cu_{\uparrow}^{2+}O_4^{2-}}$ (or $\mathrm{Cu_{\downarrow}^{2+}O_4^{2-}}$) to the adjacent complex $\mathrm{Cu_{\uparrow}^{2+}O_4^{2-}}$ (or $\mathrm{Cu_{\downarrow}^{2+}O_4^{2-}}$) depends on time *t* which pinned vortex-like excitation is found in magnetic complex. Diffusion coefficient of localized defects $D_{pv} \approx w \approx a^2/t$ does not depend on temperature (*a* is distance between two nearest ions $\mathrm{Cu_{\uparrow}^{2+}}$ (or two $\mathrm{Cu_{\downarrow}^{2+}}$), $t \sim \hbar/\Delta\varepsilon$, and width of energy band is $\Delta\varepsilon$). Using expression for diffusion coefficient of moving "defecton" in insulator $D_{mv}(T) \sim V^2 \Theta^8 / T^9$, where $V \sim a\Delta\varepsilon/\hbar$ is velocity of "defecton" with width of energy band $\Delta\varepsilon$, Θ is the Debye temperature, in Ref.[18] it was shown that quantum diffusion at the temperature $T \leq T_{AL}(p_{sh})$ leads to the transition of localized defects to moving "defectons". This transition occurs at lowering temperature, and can be found from equality $D_{mv}(T_f) = D_{pv}$:

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[3] For a review of the data on such complexes see papers J.Perumareddi et al. in J.Am.Chem.Phys. Soc. 85, 249 (1963); and H.B.Gray and C.J.Ballhausen, ibid. p.260.

[4]. Here $(\uparrow)$ or $(\downarrow)$ indicates that the ion $\mathrm{Cu^{3+}}$ takes the place of a $\mathrm{Cu_{\uparrow}^{2+}}$ (or $\mathrm{Cu_{\downarrow}^{2+}}$) ion from magnetic sublattice of copper ions.

$$T_{AL}(p_{sh}) \sim \Theta(\Delta\varepsilon/\Theta)^{1/9} . \tag{5}$$

Our "defecton" is vortex-like excitation ($v_{\downarrow}$ with clockwise motion of hole or $v_{\uparrow}$ with counterclockwise motion of hole) with energy ε_0, and width of energy band is $\Delta\varepsilon \sim p_{sh}\varepsilon_0$. Contribution of Cu^{3+} ions into the Debye temperature Θ_0 for undoped $\mathrm{CuO_2}$ plane is $\Theta \sim p_{sh}\Theta_0$. From (5) we see that transition from *pv* to moving vortices occurs at lowering temperature $T \le T_{AL}(p_{sh})$ with

$$T_{AL}(p_{sh}) \approx p_{sh}\Theta_0(\varepsilon_0/\Theta_0)^{1/9} . \tag{6}$$

At $T < T_{AL}(p_{sh})$ the moving of vortex-like excitation $v_{\downarrow}$ (or $v_{\uparrow}$) via oxygen ions within proper magnetic sublattice of $\mathrm{Cu}_{\uparrow}^{2+}$ (or $\mathrm{Cu}_{\downarrow}^{2+}$) in the $\mathrm{CuO_2}$ plane leads to transitions of nonmagnetic complex into magnetic one and vice versa. For example, transitions of $v_{\downarrow}$ and $v_{\uparrow}$)

$$[\mathrm{Cu}_{\uparrow}^{2+}(x_2,y_2)\mathrm{O}_4^{2-} + v_{\downarrow}] + \mathrm{Cu}_{\uparrow}^{2+}(x_4,y_4)\mathrm{O}_4^{2-} \to$$

$$\to \mathrm{Cu}_{\uparrow}^{2+}(x_2,y_2)\mathrm{O}_4^{2-} + [v_{\downarrow} + \mathrm{Cu}_{\uparrow}^{2+}(x_4,y_4)\mathrm{O}_4^{2-}]$$

$$[\mathrm{Cu}_{\downarrow}^{2+}(x_1,y_1)\mathrm{O}_4^{2-} + v_{\uparrow}] + \mathrm{Cu}_{\downarrow}^{2+}(x_3,y_3)\mathrm{O}_4^{2-} \to$$

$$\to \mathrm{Cu}_{\downarrow}^{2+}(x_1,y_1)\mathrm{O}_4^{2-} + [v_{\uparrow} + \mathrm{Cu}_{\downarrow}^{2+}(x_3,y_3)\mathrm{O}_4^{2-}]$$

leads to two transitions:

i) to transition of nonmagnetic complex $[\mathrm{Cu}_{\uparrow}^{2+}(x_2,y_2)\mathrm{O}_4^{2-} + v_{\downarrow}]$ (or $[\mathrm{Cu}_{\downarrow}^{2+}(x_1,y_1)\mathrm{O}_4^{2-} + v_{\uparrow}]$) into magnetic one: $\mathrm{Cu}_{\uparrow}^{2+}(x_2,y_2)\mathrm{O}_4^{2-}$ (or $\mathrm{Cu}_{\downarrow}^{2+}(x_1,y_1)\mathrm{O}_4^{2-}$),

ii) and to transition of nearest magnetic complex $\mathrm{Cu}_{\uparrow}^{2+}(x_4,y_4)\mathrm{O}_4^{2-}$ or $\mathrm{Cu}_{\downarrow}^{2+}(x_3,y_3)\mathrm{O}_4^{2-}$ into nonmagnetic one: $\mathrm{Cu}_{\uparrow}^{2+}(x_4,y_4)\mathrm{O}_4^{2-} \to [\mathrm{Cu}_{\uparrow}^{2+}(x_4,y_4)\mathrm{O}_4^{2-} + v_{\downarrow}]$ (or $\mathrm{Cu}_{\downarrow}^{2+}(x_3,y_3)\mathrm{O}_4^{2-} \to [\mathrm{Cu}_{\downarrow}^{2+}(x_3,y_3)\mathrm{O}_4^{2-} + v_{\uparrow}]$).

From Eq. (6) it is seen that temperature $T_{AL}(p_{sh})$ of transition $\mathrm{CuO_2}$ plane to the vortex metal state depends only on parameters Θ_0 and ε_0 for undoped $\mathrm{CuO_2}$ plane. This means that line $T_{AL}(p_{sh})$ is universal line for UD copper HTSs.

For the first time at lowering temperature within the AFM state of UD cuprates the magnetic transitions at $T<T_N(p)$ into a spin-glass-like state $T \le T_g(p_{sh})$ at temperature

$$T_f(p_{sh}) = 815 p_{sh}(K) , \tag{7}$$

have been reported from μSR studies in Refs. [19,20]. At $T < T_f(p_{sh})$ the holes leave hole poor regions with sizes $L(p_{sh}) \sim p_{sh}^{-1/2}$ (with AFM correlated $\mathrm{Cu}_{\uparrow}^{2+}$ (or $\mathrm{Cu}_{\downarrow}^{2+}$) spins), and segregate into metallic (holes rich) domains with length about 20 Å. For example, for phase coexistence (see Eq.(1)) p_{cr}=0.02 and $T_f(p_{cr}) \approx 17K$ for $\mathrm{La_{2-\mathit{x}}Sr_{\mathit{x}}CuO_4}$ with the single $\mathrm{CuO_2}$ plane [19], and $p_{cr} = 0.035$, $T_f(p_{cr}) \approx 25K$ for bilayer system $\mathrm{Y}_{1-x}\mathrm{Ca}_x\mathrm{Ba_2Cu_3O_{6.02}}$ [20].

These observations indicate that at $T \le T_f(p_{sh})$ the holes segregation into metallic domains is property of hole dynamics within $\mathrm{CuO_2}$ plane, and even though $T_f(p_{sh})$ does not depend on number of $\mathrm{CuO_2}$ planes. So, we can suppose that at $T<T^*(p_{sh})$ line $T_f(p_{sh})$ is universal line for PG state of UD cuprates as for $p_{sh} \le p_{cr}$, and so for $p_{sh}^* \ge p_{sh} \ge p_{cr}$ where $T^*(p)|_{p=p_{sh}^*} = T_f(p)|_{p=p_{sh}^*}$, and

$$T_{AL}(p_{sh}) = T_f(p_{sh}) . \tag{8}$$

This means that transition of pinned vortex-like excitations to moving ones leads to transition of *U* stripes of $\mathrm{CuO_2}$ plane into vortex metal state and occurs at lowering temperature

$$T \le T_f(p_{sh}) \le T^*(p_{sh}) .$$

3. CONCLUSION

At $p_{sh}>p_{cr}$ quantum diffusion of vortex-like excitations in PG state at $T \le T_f(p_{sh})$ resembles the Nernst effect taking place in LT superconductors at $T<T_c$, and was observed in PG state of UD copper HTS in the non-zero magnetic field [21,22]. The Nernst signal may be caused by the motion of quasiparticles and vortices, so long time origin of the strong Nernst signal above T_c remains controversial.

At first by using thermal and Lorentz forces together in Ref. [23] for single crystal $\mathrm{La_{2-\mathit{x}}Sr_{\mathit{x}}CuO_4}$ (x=0.11, p_{sh}~$x/2 \approx 0.055$, T_c=29.3K) was shown that the effects of Lorentz force on the Nernst effect in normal state (80K) are related to the direction of magnetic field (see Fig. 8 in [23]). This observation may be explained only by the motion of pinned vortices under heating power 1.0mW, and the vortex structures are different below and above T_c. Really, as it is shown above, at $T<T_f(p_{sh})$ vortices are two-dimensional, and their vortex-antivortex pairing at $T \le T_{BKT}(p_{sh})$ leads to 2D superconducting fluctuations. Only further lowering temperature leads to transition to three-dimensional charge carriers at

$$T \le T_g(p_{sh})$$

or to their pairing at $T \le T_{3D}(p_{sh}) < T_{BKT}(p_{sh})$.

This means that properties of pseudogap state at $T^*(p_{sh}) > T > T_{3D}(p_{sh})$ are conditioned by properties of hole dynamics within $\mathrm{CuO_2}$ plane:

At temperature $T^*(p_{sh}) > T$ two-dimensionality of $\mathrm{CuO_2}$ plane leads to the formation of *D*- and *U* stripes, that indicates on the copper nature of holes and on existence of "molecules" $\mathrm{Cu^{3+}O_4^{2-}}$. For these molecules, as for other d^8-plane square complexes, the tendency towards distortion of the copper-oxygen planes is inherent[5].

In *U*-stripes two-dimensionality leads to transitions of “molecules” $\mathrm{Cu}^{3+}\mathrm{O}_4^{2-}$ into magnetic complexes $\mathrm{Cu}_{\uparrow}^{2+}\mathrm{O}_4^{2-}+v_{\downarrow}$ (or $\mathrm{Cu}_{\downarrow}^{2+}\mathrm{O}_4^{2-}+v_{\uparrow}$) with pinned vortices.

Further lowering temperature $T \le T_f(p_{sh})$ leads to quantum transition of *U*-stripes from the insulator to the metal state with moving vortices which are mobile charge carriers compatible with the antiferromagnetism of the doped $\mathrm{CuO_2}$ plane. Line $T_f(p_{sh})$ is universal line of a common phase diagram for PG state of UD cuprates.

Further lowering temperature $T \le T_{BKT}(p_{sh})$ leads to 2D superconducting fluctuations in $\mathrm{CuO_2}$ plane at vortex-antivortex pairing, and $T_{BKT}(p_{sh})$ is the second universal line for PG state of UD cuprates.

Only further lowering temperature leads to strong interplane interaction and to transition to three-dimensional charge carriers with three-dimensional superconducting fluctuations at

$T \le T_{3D}(p_{sh}),\ T_{3D}(p_{sh}) < T_{BKT}(p_{sh}).$

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[5] Recently (see H.Mukuda et. al, Phys.Rev. Lett. 96, 087001, 2006) multilayered HTS without stripe structure of $\mathrm{CuO_2}$ plane was discovered. This means that in these structures holes have oxygen nature.

КВАНТОВАЯ ПРИРОДА НЕФЕРМИЕВСКИХ НОСИТЕЛЕЙ ЗАРЯДА В ПСЕВДОЩЕЛЕВОМ СОСТОЯНИИ ВЫСОКОТЕМПЕРАТУРНЫХ СВЕРХПРОВОДНИКОВ

Г.Г. Сергеева

Для псевдощелевого состояния слабо допированных купратных высокотемпературных сверхпроводников (ВТСП) со страйповой структурой медь-кислородных плоскостей развито описание *U*-страйпа как двумерного состояния с вихреподобными возбуждениями. При высоких температурах эти вихри закреплены на медь-кислородных комплексах, и при понижении температуры $T \leq T_f(p)$ происходит переход от закрепленных вихрей к подвижным (*p* – концентрация допирования). Показано, что этот переход является результатом квантовой диффузии, которая для квантовых кристаллов была предсказана А.Ф. Андреевым и И.М. Лифшицем (1969). Квантовая диффузия приводит к нефермиевским носителям заряда и к двум универсальным линиям на общей фазовой диаграмме слабо допированных купратов. Этот подход позволяет предположить, что псевдощелевое состояние слабо допированных купратов определяется только свойствами медь-кислородной плоскости.

КВАНТОВА ПРИРОДА НЕФЕРМІЇВСЬКИХ НОСІЇВ ЗАРЯДУ У ПСЕВДОЩІЛИННОМУ СТАНІ ВИСОКОТЕМПЕРАТУРНИХ НАДПРОВІДНИКІВ

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Для псевдощілинного стану слабо допованих високотемпературних надпровідників (ВТНП) із страйповою структурою мідь-кисневої площини розвинуто опис *U*-страйпу як двовимірного стану із збудженнями, які подібні до вихорів. При великих температурах ці вихорі закріплені мідь-кисневими комплексами, і при зниженні температури $T \leq T_f(p)$ має місто їх перехід до мобільного стану (*p* – концентрація допування). Показано, що цей перехід є наслідком квантової дифузії, яка для квантових кристалів була передбачена О.Ф. Андрєєвим та І.М. Ліфшицем (1969). Квантова дифузія призводить до неферміївських носіїв заряду та до двох універсальних ліній на загальній фазовій діаграмі слабо допованих купратів. Така модель дозволяє припустити, що псевдощілиний стан слабо допованих купратів залежить тільки від властивостей мідь-кисневої площини.