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The possibility of realizing room-temperature superconductivity in high-T_c cuprates in their two-dimensional sandwich layers

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Based on the predictions of the theory of a superfluid Bose-liquid of unconventional (tightly-bound) Cooper pairs, we consider the possibility of realizing room-temperature superconductivity in distinctive high-T_c cuprate materials containing many grain boundaries,interfaces and planes in the layered blocks. We argue that such high-T_c materials (e.g., Bi/Pb-based high-T_c cuprates) are the most promising and have certain favorable properties, which can serve as a possible guide in the search for persisting room-temperature superconductivity maintained in two-dimensional (2D) regions (e.g. at planar sheets or plates). We show that the superconducting transition temperature T_c is much lower in the bulk of high-T_c cuprates than at planes in them; and the three-dimensional (3D) superconductivity in these materials is destroyed above the bulk T_c, while the 2D superconductivity is maintained at grain boundaries and interfaces and in the multiplate blocks up to room temperature at atmospheric pressure. We predict that the crossover from bulk to surface Bose-liquid superconductivity in the alternating 3D/2D sandwich layers might be possible route to room-temperature superconductivity in promising high-T_c cuprate materials. Various experiments on some families of high-T_c cuprates confirm the theory of Bose-liquid superconductivity and the signs of the superconducting transitions at temperatures well above the bulk T_c and sometimes close to room temperature.

Keywords: high-T_c cuprates, Bose superfluids, grain boundaries, interfaces and planes/sheets, three- and two-dimensional sandwich layers, room-temperature superconductivity.

Можливість реалізації надпровідності при кімнатній температурі у високотемпературних купратах в їх двовимірних сендвіч-шарах. *С.Джуманов, А.Л.Соловйов, Р.В.Вовк, Б.В.Гріньов, Ш.С.Джуманов*

Базуючись на передбаченнях теорії надплинної бозе-рідини нетрадиційних (міцно звіязаних) куперівських пар, ми розглядаємо можливість реалізації надпровідності при кімнатній температурі в характерних високотемпературних купратних матеріалах, які містять багато меж зерен, інтерфейсів і площин у шаруваті блоки. Ми стверджуємо, що такі високотемпературні матеріали (наприклад, високотемпературні купрати на основі Bi/Pb) є найбільш перспективними та мають певні сприятливі властивості, які можуть служити можливим орієнтиром у пошуку стійкої надпровідності при кімнатній температурі, що підтримується в двох-вимірні (2D) області (наприклад, на плоских листах або плитах). Ми показуємо, що температура надпровідного переходу T_c значно нижча в об'ємі високотемпературних купратів, ніж у площинах у них; і тривимірна (3D) надпровідність у цих матеріалах руйнується вище об'ємної T_c, у той час як 2D надпровідність зберігається на границях зерен і поверхнях розділу та в багатопластинкових блоках до кімнатної температури при атмосферному тиску. Ми передбачаємо, що перехід від об'ємної до поверхневої надпровідності бозе-рідин у чергуванні 3D/2D сендвіч-шарів може бути можливим шляхом до надпровідності при кімнатній температурі в багатообіцяючих високотемпературних купратних матеріалах. Різноманітні експерименти на деяких сімействах високотемпературних купратів підтверджують теорію надпровідності бозе-рідин і ознаки надпровідних переходів при температурах, значно вищих за об'ємну T_c і іноді близьких до кімнатної.

1. Introduction

The phenomenon of superconductivity has been discovered since the last century in many different substances ranging from simple metals to complex copper oxides (cuprates). The discovery of high-temperature superconductivity in La-based cuprates with the superconducting transition temperature $T_c \simeq 35$ K [1] and the subsequent dramatic increase of T_c in other discovered Y-, Bi- and Hg- based cuprate compounds to above 90 K [2], 110 K [3] and 130 K [4] opened up the possibility of increasing the highest value of T_c to well over 100 K and inspired researchers to search for room-temperature superconductors. However, for a long time, despite considerable theoretical and experimental efforts [5–12], the increasing of T_c up to room-temperature in various families of high-T_c cuprate superconductors was remained a difficult problem.

First, Chu et al. [5] found that when the Hg-based cuprate $HgBa_2Ca_{n-1}Cu_nO_{2n+4}$ superconductor was subjected to pressures up to 150 kbar, an increase in T_c up to 153 K was observed in this system. In a further experiment, the cuprate superconductor $HgBa_2Ca_{m-1}Cu_mO_{2m+2+d}$ was subjected to quasi-hydrostatic pressure up to 45 GPa and the highest value of T_c reaching up to 164 K was reported by Gao et al. [6]. Later, Takeshita et al. [10] noted that the T_c values reported in the above studies at high-pressures are usually defined as the temperature at which the drop in resistivity begins, i.e. at the T_c values determined in these studies, zero resistivity was not observed. They reported that zero resistivity is maintained up to 153 K in high-T_c cuprates under almost hydrostatic pressure of 15 GPa and the superconducting transition temperature T_c under such a high pressure reaches 153 K; this is the actual highest T_c record obtained so far. The experimental data obtained in the studies on the effect of high hydrostatic pressure on the various electric transport mechanisms in high-T_c cuprates were discussed in [13]. Recently, high-T_c superconductivity has been discovered in other classes of new materials, such as in hydrogen- and carbon-rich materials, at temperatures close to room temperature and at extremely high pressures [14, 15]. In particular, the superconducting transitions with $T_c \simeq 250–260$ K in the lanthanum hydride ($LaH_{10\pm x}$) at high pressures of 180–200 GPa were reported for the first time [14]. Then the room-temperature superconductivity was found in the carbonaceous sulfur hydride (C–S–H) system with a maximum superconducting transition temperature of 287.7±1.2 K achieved at very high pressures of the order of 267±10 GPa [15]. However, room-temperature superconductors at such high pressures will not have immediate practical applications. In this regard, some distinctive families of superconducting cuprates may be the most promising and have certain favorable properties, which serve as a possible guide to the search for room-temperature superconductivity maintained in specially-grown specimens of such high-T_c materials at atmospheric pressure.

Until now, it is often believed that Little's model of high-temperature superconductivity in one-dimensional organic compounds [16] and Ginzburg's model of two-dimensional (2D) alternating conducting/insulating sandwich layers [17] may be possible paths to room-temperature superconductivity. However, these models are based on the predictions of the BCS-like theory of Fermi-liquid superconductivity. In contrast, the doped high-T_c cuprates can be in the regime of Bose-liquid superconductivity. In fact, both experimental and theoretical studies [7, 18–21] provide more and more evidence, that the superconducting state in high-T_c

cuprates is not just unusual, but actually a superfluid state of a Bose-liquid of charged bosons (tightly-bound Cooper pairs), since these high-T_c materials undergo a λ-like superconducting transition at T_c [18, 19] (in contrast to the BCS-like transition).

In this work, we study the possibility of realizing room-temperature superconductivity in typical high-T_c cuprate materials containing many grain boundaries, interfaces and planes in multi-lamellar blocks representing alternating three-dimensional (3D)/2D sandwich layers. We believe that the relevant charge carriers in doped cuprates are polarons; therefore, the phenomenon of high-T_c superconductivity in these materials is due to the superfluidity of polaronic (bosonic) Cooper pairs and differs from the superconductivity of a BCS-type Fermi-liquid. We predict the possibility of realizing room-temperature superconductivity well above the bulk T_c in alternating 3D non-superconducting and 2D superconducting sandwich layers in specially-grown high-T_c cuprates; in this case, in 3D regions, the destruction of high-T_c superconductivity occurs above the bulk T_c, while in 2D layers (i.e., at grain boundaries, interfaces, and flat layers), the regime of high-temperature superconductivity is retained up to room temperature.

Distinctly different superconducting transition temperatures in 3D and 2D Bose systems

Undoped cuprates are charge-transfer (CT)-type Mott insulators [22]. The nature and properties of charge carriers introduced into the polar materials by doping are strongly modified during their interaction with the lattice vibrations. Hole carriers doping cuprates are self-trapped when they are strongly coupled to optical phonons and become strongly coupled large polarons [23]. In the doped cuprates, the self-trapping of hole carriers is favorable just like the self-trapping of free holes in ionic crystals of alkali halides [24, 25]. When the Fermi energy ε_F of polarons is comparable with the energy ε_A of the attractive interaction between them, the Cooper pairing of polaronic carriers results in the formation of bosonic (polaronic) Cooper pairs in the normal state of high-T_c cuprates [20]. Therefore, the observed superconducting transition temperature T_c in the bulk of these materials is determined from the solutions of the following self-consistent integral equations of a 3D superfluid Bose liquid [26]:

$$\frac{2}{\gamma_B} = \int_0^{\xi_{BA}} \sqrt{\{}\varepsilon/\xi_{BA} \; \frac{\coth\left[\sqrt{(\varepsilon+\tilde{\mu}_B)^2 - \Delta_B^2}/2k_BT\right]}{\sqrt{(\varepsilon+\tilde{\mu})^2 - \Delta_B^2}} d\varepsilon, \tag{1}$$

$$\frac{2\rho_B}{D_B} = \tag{2}$$
$$= \int_0^{\infty} \sqrt{\varepsilon} \left\{ \frac{\varepsilon + \tilde{\mu}_B}{\sqrt{(\varepsilon + \tilde{\mu}_B)^2 - \Delta_B^2}} \coth\left[\frac{\sqrt{(\varepsilon + \tilde{\mu}_B)^2 - \Delta_B^2}}{2k_BT}\right] - 1 \right\} d\varepsilon,$$

where $\gamma_B = D_B\tilde{V}_B\sqrt{\xi_{BA}}$ is the interboson coupling constant in a 3D superfluid Bose-liquid; $D_B = m_B^{3/2}/\sqrt{2}\pi^2h^3$ is the density of states of bosons; m_B is the mass of bosons; $\tilde{V}_B = V_{BA} - V_{BR}/\ \ [1 + D_BV_{BR}(\sqrt{\xi_{BR}} - \sqrt{\xi_{BA}}\}]$ is the effective interaction potential between bosons; ξ_{BA} and ξ_{BR} are the cutoff parameters for attractive V_{BA} and repulsive V_{BR} parts of the interboson interaction potential; ρ_B is the density of attracting (superfluid) bosons; $\tilde{\mu}_B$ is the chemical potential measured relative to the Hartree-Fock quasipartical energy; Δ_B is the coherence parameter (i.e. superfluid order parameter) of condensed bosons.

The superconducting transition temperature T_c^{2D} in 2D planes and sheets in high-T_c cuprates is determined from the solutions of the following integral equations of a 2D superfluid Bose-liquid [26]

$$\frac{2}{\gamma_B} = \int_0^{\xi_{BA}} \frac{\coth\left[\sqrt{(\varepsilon + \tilde{\mu}_B)^2 - \Delta_B^2}/2k_BT\right]}{\sqrt{(\varepsilon+\tilde{\mu}_B)^2 - \Delta_B^2}} d\varepsilon \ , \tag{3}$$

$$\frac{2\rho_B}{D_B} = \tag{4}$$
$$= \int_0^{\infty} \left\{ \frac{\varepsilon+\tilde{\mu}_B}{\sqrt{(\varepsilon+\tilde{\mu}_B)^2 - \Delta_B^2}} \coth\left[\frac{\sqrt{(\varepsilon + \tilde{\mu}_B)^2 - \Delta_B^2}}{2k_BT}\right] - 1 \right\} d\varepsilon,$$

where $\gamma_B = D_B\tilde{V}_B$ is the interboson coupling constant in a 2D superfluid Bose-liquid; $D_B = m_B/2\pi h^3$; ρ_B is the density of attracting (superfluid) bosons in a 2D Bose-liquid.

In the case of 3D Bose superfluids, numerical solutions of Eqs. (1) and (2) can be obtained for arbitrary γ_B. It is useful, however, to obtain an approximate analytical expression for T_c. Using the analytical solutions of Eqs. (1) and (2) near T_c and in the temperature range somewhat below T_c, a simple approximate expression can be obtained for

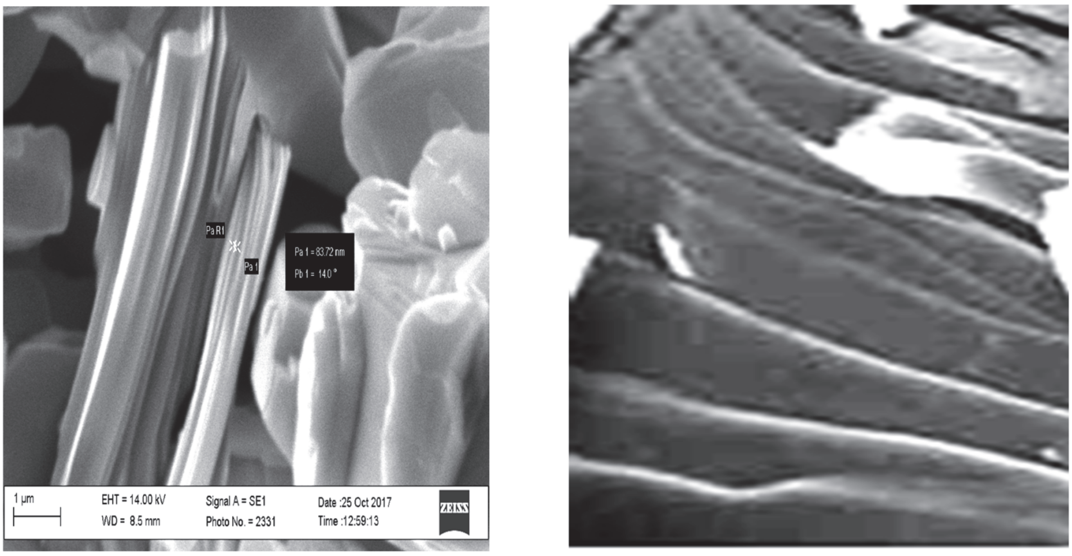

Fig. 1. Lamellar microstructure of high-T_c cuprate superconductor Bi/Pb (2:2:19:20) with the stack of many blocks [27].

T_c at $\gamma_B < 1$ [26]. At $\gamma_B \geq 0.3$ and $\gamma_B < 1$, this expression for the superconducting transition temperature T_c in the bulk of high-T_c cuprates has the form

$$T_c \simeq T^*_{BEC}\left[1 + c\gamma_B\sqrt{\sqrt{2}\ k_B T^*_{BEC}/\xi_{BA}}\right], \quad (5)$$

where $T^*_{BEC} = 3.31h^2\rho_B^{2/3}/k_B\ m^*_B$ is the renormalized Bose-Einstein condensation temperature in a 3D Bose liquid, $c = \pi^{3/2}/3.918$.

In the case of 2D Bose superfluids, the solutions of Eqs. (3) and (4) at $T \to T_c^{2D}$ are obtained analytically [7, 26] and the actual T_c^{2D} in the cuprates for arbitrary γ_B is determined from the relationship

$$T_c^{2D} = -\frac{T^*_0}{\ln[1 - \exp(-2\gamma_B/(2 + \gamma_B))]}, \quad (6)$$

where $T^*_0 = 2\pi h^2\rho_B/\ k_B m^*_B$.

The possibility of realizing room-temperature superconductivity in sandwich-type high-T_c cuprate materials

Experimental studies of the microstructure of a new family of Bi/Pb — based high-T_c cuprates $Bi_{1.7}Pb_{0.3}Sr_2Ca_{(n-1)}Cu_nO_y$ (where $n = 3$–20) synthesized by melt technology under the influence of solar energy [12, 27] in a solar furnace (in Parkent) show that these materials consist of many layered blocks (see Fig. 1). These blocks, in turn, contain coupled stacks of many quasi-2D plates, so that the multi-lamellar blocks are alternating three-dimensional/two-dimensional sandwich layers.

In order to determine the sharply different superconducting transition temperatures in the bulk and 2D planes (sheets) in sandwich-type high-T_c cuprates, we estimate T_c and T_c^{2D}, assuming that the mass m_p of polaronic carriers is of the order of $2m_e$ (where m_e is the mass of free electrons); first, the bosonic Cooper pairs having the mass $m_B = 2m_p$ are formed in the normal state, and then the interacting bosons (polaronic Cooper pairs) with the renormalized mass $m^*_B > m_B$ condense into a Bose superfluid at $T \leq T_c$ and $T \leq T_c^{2D}$. By taking $m_p \simeq 2m_e$, $m_B = 2m_p$, $m^*_B \simeq 1.05m_B$ and $\rho_B \simeq 4\cdot10^{19}\text{cm}^{-3}$ for 3D high-T_c cuprates, we find $T^*_{BEC} \simeq 81.7$ K. Next, we estimate T_c, assuming that $\xi_{BA} = h\omega_0$ (where ω_0 is the frequency of the optical phonons in high-T_c cuprates), and that bosonic Cooper pairs in the intermediate coupling regime ($0.3 < \gamma_B < 1$) interact with optical phonons having relatively low energy $h\omega_0 \simeq 0.03$ eV. Under these assumptions, we can use expression (5) to calculate the bulk T_c in high-T_c cuprate materials. Then, assuming that at $\gamma_B = 0.7$, we find $T_c \simeq 1.508T^*_{BEC} \simeq 123$ K. We can now estimate T_c^{2D}, assuming that $m_p \simeq 3m_e$, $m_B = 2m_p$, $m^*_B \simeq 1.05m_B$ and $\rho_B \simeq 2\cdot10^{13}\text{cm}^{-2}$ for 2D planes and sheets in high-T_c cuprates. Using the above values of the relevant parameters, we obtain $T^*_0 \simeq 176$ K. If in expres-

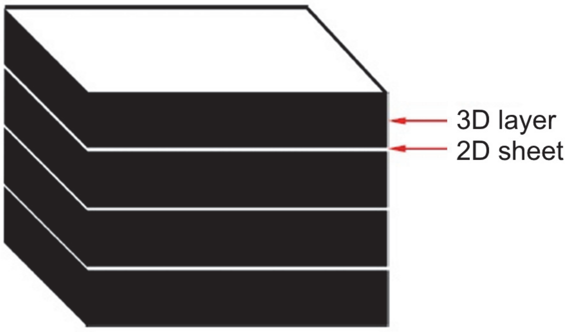

Fig. 2. Alternating 3D superconducting/2D superconducting sandwich layers in bosonic high-T_c cuprate superconductors below the bulk T_c.

sion (6) we take the same value of $\gamma_B = 0.7$ for a 2D Bose superfluid, we find $T_c^{2D}\simeq 1.105T_0^*\simeq 195$ K. The above predictions of the theory of 3D and 2D Bose superfluids indicate that the expected value of T_c in the bulk of high-T_c cuprates is much lower than the expected value of T_c^{2D} at planes and planar sheets in these materials. We argue that the 3D regions in the considered high-T_c cuprates become non-superconducting above the bulk $T_c(=T_c^{3D})$, but the Bose-liquid superconductivity is still preserved in 2D regions at much higher T_c. This 2D Bose-liquid superconductivity maintaining at grain boundaries, interfaces and planes in multi-plate blocks of high-T_c cuprate materials may be encouraging in achieving room-temperature superconductivity at atmospheric pressure. Here we state that in specially grown samples of high-temperature cuprate superconductors, many grain boundaries parallel to each other, interfaces and planes or sheets in multi-plate blocks in alternating 3D superconducting/2D superconducting sandwich layers below the bulk T_c (Fig. 2) and in alternating 3D non-superconducting/2D are involed superconducting sandwich layers above T_c (Fig. 3). As seen in Fig. 3, the transition from the bulk to surface Bose-liquid superconductivity in the alternating 3D non-superconducting/2D superconducting sandwich layers can be a favorable path to realizing room-temperature superconductivity in high-T_c cuprates.

One can expect that the critical temperature of the superconducting transition in 2D sheets of new sandwiches in high-T_c cuprates shown in Fig. 3 can reach room temperature at certain values of ρ_B and γ_B. If we take $\rho_B\simeq 3\cdot 10^{13}\text{cm}^{-2}$ and $\gamma_B = 0.75$ for 2D layers of the above sandwiches, we find

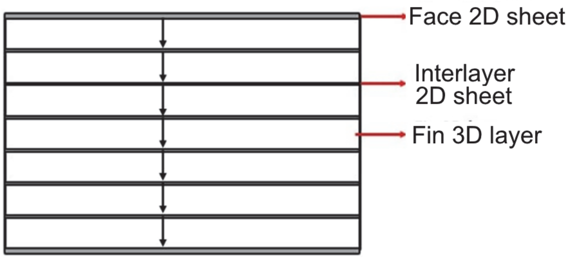

Fig. 3. Alternating 3D non-superconducting/2D superconducting sandwich layers in bosonic cuprate superconductors above the bulk T_c. Bold-type arrows indicate a transition from 3D non-superconducting (metallic) state to 2D superconducting state in these systems.

$T_0^*\simeq 265$ K and $T_c^{2D}\simeq 1.154T_0^*\simeq 306$ K under the above assumptions of $m_p\simeq 3m_e$, $m_B = 2m_p$, $m_B^*\simeq 1.05m_B$. It follows that the room temperature superconductivity can be realized at grain boundaries, interfaces and planes/sheets in multi-plate blocks in some families of high-T_c cuprates. In fact, there is experimental evidence that superconducting transition temperatures significantly exceed bulk T_c in high-temperature cuprates based on Y, Bi, and Hg. In particular, experimental results on anomalous transitions of resistivity between 125 and 260 K in high-T_c cuprates $Y_3Ba_4Cu_7O_x$ (with bulk $T_c\simeq 90$ K) indicate that superconductivity above the bulk T_c occurs at the grain boundaries in these systems [28] in accordance with the prediction of the above sandwich model. In addition, there is also experimental evidence for the retention of high-temperature superconductivity much higher than the bulk T_c in other families of cuprate superconductors, where resistive transitions were also observed at a temperature of about 260 K [29]. Most importantly, the possibility of traces of superconductivity at temperatures $T\gg T_c$ and sometimes close to room temperature was observed in the systems $HgBa_2Ca_{n-1}Ca_nO_{2n+2+\delta}$ and $Bi_2Sr_2CaCu_2O_8$ [29]. These experimental findings are also indicative of the superconducting transitions taking place close to room temperature at 2D grain boundaries, interfaces and planes/sheets in multi-plate blocks in high-T_c cuprates based on Hg and Bi, according to the sandwich model shown in Fig. 3. We believe that some evidence of room-temperature superconductivity has been observed in samples of high-T_c Bi/Pb-based cuprates synthesized by using the new melt technology under the influence of concentrated solar energy, which contain many grain boundaries, interfaces and multi-plate blocks [30] (see Fig. 1).

Conclusions

We studied the possibility of realizing room-temperature superconductivity in sandwich-type high-T_c cuprate materials containing many grain boundaries, interfaces and planes/sheets in multi-plate blocks. We have shown that the theory of Bose-liquid superconductivity predicts the possible route in the search for room-temperature superconductivity in such high-T_c materials. We have found that the critical temperature T_c of the superconducting transition in high-T_c cuprates is much higher in 2D regions than in the bulk. In high-T_c cuprate materials synthesized using the new melt technology, many grain boundaries, interfaces and multi-plate blocks are involved in alternating 3D non-superconducting/2D superconducting sandwich layers above than the bulk T_c. This sandwich model for room-temperature superconductivity is based on the predictions of the theory of 3D and 2D Bose superfluids and on the transition from 3D regime to 2D regime of superconductivity in the alternating 3D/2D sandwich layers in high-T_c cuprates. We conclude that the highest T_c up to room temperature can be reached in 2D planes and sheets in such sandwich-type high-T_c cuprates. We argue that the specially-grown-specimens of high-T_c cuprates based on Bi and Hg can be used in the search for room-temperature superconductivity. We compared our results on superconducting transitions above bulk T_c in various high-T_c cuprates with experimental data indicating the retention of high-temperature superconductivity above bulk T_c up to room temperature in some families of high-temperature cuprates.

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