I. INTRODUCTION

Finding the room temperature superconductors has been an elusive dream of scientists in the field of condensed matter physics. In 1986, the discovery of high temperature cuprate superconductivity by Bednorz and Müller shocked the superconductivity community and rekindled the dream of room-temperature superconductivity. Since then, great efforts have been devoted to finding out new materials with a higher critical temperature. Many cuprate superconductors have since been discovered and the highest temperature superconductor was HgBa$_2$Ca$_2$Cu$_3$O$_{8+\delta}$ with $T_c = 138$ K. Its $T_c$ can be increased as high as 164 K under a high pressure of about 30 GPa. Later, several materials have been claimed to be room-temperature superconductors which have been quickly proved to be false. However, how to enhance the superconducting transition temperature is always one of central concerns in the field of superconductivity.

In 2008, Japanese researchers discovered the superconductivity in the iron-oxypnictide family of compounds. Like the Cu-based superconductors, the new superconductors have layered atomic structures and can conduct electricity without resistance at relatively high temperatures than the conventional low-temperature superconductors. Similarly, the new discovery has triggered intensive research worldwide and the maximum critical temperature has been raised from the initial report of $T_c = 26$ K in LaO$_{1-x}$Fe$_x$FeAs to about 55 K in SmO$_{1-x}$Fe$_x$FeAs. Facing the rapid increase of $T_c$, some researchers seem too optimistic about the new discovery and they even claimed that these compounds could be useful for developing room-temperature superconductivity. In fact, more than one year ago, we proved theoretically that the maximum $T_c$ of the new iron arsenide superconductors is very difficult to reach 60 K by means of elements substitution or by applying hydrostatic pressure, and this prediction is still correct up to now.

In addition, physicists considered that a high pressure can make the hydrogen molecules into atoms and make it a metallic conductor. Moreover, it was predicted according to the BCS theory in 1968 by Ashcroft that solid metallic hydrogen may be superconducting at high temperature, perhaps even room temperature. However, to get metallic hydrogen is still a distant dream, not to mention the realization of the superconductivity. Based on our theory, we would like to point out that even if there exists metallic hydrogen, it is also impossible to exhibit the superconductivity at any low temperature.

In this paper, the discussion of enhancement of superconductivity is presented in the framework of the real-space superconducting vortex lattices. We show that the effective $c$-axis lattice constant play a key role in promoting the superconducting transition temperature in the layered superconductors.

II. A COMPARISON BETWEEN TWO SUPERCONDUCTING THEORIES

A. BCS theory of superconductivity

In the framework of the BCS theory, the superconducting current is carried by the so-called Cooper pairs of electrons which are held together by lattice vibrations...
(an exchange of phonon) in the material. The usual analysis in the BCS theory relies on a momentum-space picture, the Cooper pairs are formed in momentum space (k-space) and the paired electrons have opposite spin and opposite momentum (k↑,−k↓), as shown in Fig. 1(a). Of course, if the two electrons are to remain in the same paired state forever, then they must undergo a continuous exchange of virtual phonon in the BCS picture.

Although the physics community accepts that the BCS theory can successfully describe the behaviors of most metallic superconductors, it is commonly believed that the phonon based BCS theory is invalid for the description of the behavior of the high-temperature superconductors. As pointed out by Anderson, the need for a bosonic glue (phonon) in cuprate superconductors is folklore rather than the result of scientific logic. It is well known that the superconducting electrons (as defined by BCS theory) are a momentum space order phase, while at the same time a disorder phase in real-space. From both the physics and mathematics point of view, the fundamental differences between two descriptions (one order and one disorder) of superconducting electrons imply that the BCS theory may not be scientifically self-consistent. From the perspective of the real-space correlations, two bound electrons (a Cooper pair) can separate by a coherence length of ξ up to 100 nm, which is also called the coherence length. It should be noted that there are about 10^7 randomly distributed electrons (or pairs) between them in the conventional superconductors, as illustrated in Fig. 1(b). More importantly, the Coulomb interaction is the elementary electrical force that causes two negative electrons to repel each other, hence, two important questions arise: (1) How can the real-space repulsions among electrons (or pair-pair repulsions) and the attractions among electrons and ions be eliminated to support the formation of the Cooper pairs? (2) Normally, there are two kinds of interactions in the superconducting materials, one is the very strong short-range electron-electron interactions [see Fig. 1(b)], the other is the rather weak long-range electron-phonon interactions [see Fig. 1(a)]. Now, the question is why can the stronger short-range electron-electron interactions be completely ignored in the BCS theory?

B. Wigner crystal and the real-space superconducting theory

As we know there are many theories about the cause of the superconductivity in cuprate high temperature superconductors. Unfortunately, most of these theories contradict each other and they may be on the wrong track as emphasized by Anderson. In our opinion, the natural strong repulsion between two electrons is impossible to be totally overpowering by a lattice vibration (known as a phonon) and all superconductors should share exactly the same physical reason. The present situation of one-material one-mechanism of superconductivity should be changed. In other words, a new and unified theory which can explain all superconducting phenomena has proved more important and urgent today.

With increasingly better samples and advances in experimental techniques (for example the Scanning Tunneling Microscopy), a vast amount of data from these experimental studies reveal that the superconducting electrons are more likely to congregate in some real space quasi-one-dimensional rivers of charge separated by insulating domains. Obviously, a correct and reliable theory of superconductivity has to take into account these new results. Although many researchers have been trying to replace the conventional superconducting picture (dynamic screening) with a real space picture, but how to construct a proper model related to the formation of the one-dimensional charge rivers will still be a major challenge for those devoted themselves to crack the mystery of high-temperature superconductivity.

In recent years, we have tried to propose a real space superconducting mechanism which may provide new insights into the nature of the superconductivity. In our scenarios, all the superconducting electrons can be considered as the ‘inertial electrons’ moving along some quasi-one-dimensional real-space ballistic channels, as shown in Fig. 2(a). In the previous paper, it was proved theoretically that a static one-dimensional charge stripe can be naturally formed inside the superconducting plane and the Coulomb repulsion between electrons can be suppressed completely, as indicated in Fig. 2(a).
To form a stable superconducting vortex lattice, both electron-electron repulsive interactions within the charge stripes and between the stripes should be inhibited thoroughly. The former situation was studied and resolved in one of our previous papers. Here we will pay our attention to the later situation. It will be shown that the nature of the electron-electron repulsive interaction can even be changed into an attractive type because of the positive ion background.

Our theory is based on the experimental facts that the superconducting electrons may be associated with a long-range spatial coherence charge ordered state. In order to study the stability of the superconducting vortex lattices of Fig. 2 we can consider the simplest case where the stripe-stripe interaction can be simplified as the electron-electron interaction, as shown in Fig. 3. We will show that by adjusting the parameters \( \delta \) the electron interaction can not only be repulsive but can be also attractive. Moreover, there is a special value of \( \delta \) that can lead to a completely suppression of the Coulomb repulsion, that is

\[
f_B = F_1 - F_2
\]

(1)

In the following, we will discuss how electron-electron repulsion between the two adjacent charge stripes be overcome? It is worth noting is that this is merely the
well-known Coulomb screening effect of the positive ion background. For simplicity, apart from the Coulomb repulsion between two electrons, we consider only the nearest-neighbors (both in $x$ and $y$-directions) and next-nearest neighbors (only in $x$-direction) electron-ion interactions in this study, as shown in Fig. 4. Here we analyze mainly the forces applied on the electron $A$ of Fig. 4 and the discussion is similar to another electron $B$ (not shown in this figure).

According to Fig. 4 and Fig. 3, the Coulomb forces applied to the electron $A$ can be divided into three parts. The first part is electron-electron ($A$ and $B$) repulsion which is given by

$$f_B = \frac{e^2}{4\pi \varepsilon_0 [(l + 2a)^2 + \delta^2]^{3/2}}, \quad (l = 1, 2, 3, \ldots) \quad (2)$$

The second part is contributed by the eight ions (they are marked by 1, 2, 3, 4, 5, 6, 7 and 8 in Fig. 3) and each ion carries a positive charge $ne$ around the electron $A$, they are

$$F_{x(12)} = f_1 + f_2$$
$$= -n \frac{e^2}{4\pi \varepsilon_0 [(a/2)^2 + \delta^2]^{3/2}}, \quad (3)$$

$$F_{x(34)} = f_3 + f_4$$
$$= n \frac{e^2}{4\pi \varepsilon_0 [(a/2)^2 + (a - \delta)^2]^{3/2}}, \quad (4)$$

$$F_{x(56)} = f_5 + f_6$$
$$= -n \frac{e^2}{4\pi \varepsilon_0 [(a/2)^2 + (a + \delta)^2]^{3/2}}, \quad (5)$$

$$F_{x(78)} = f_7 + f_8$$
$$= n \frac{e^2}{4\pi \varepsilon_0 [(a/2)^2 + (2a - \delta)^2]^{3/2}}. \quad (6)$$

The resultant force of this part on the electron $A$ can be expressed as:

$$F_x = F_{x(12)} + F_{x(34)} + F_{x(56)} + F_{x(78)}. \quad (7)$$

The third part is contributed by the other eight ions around the electron $B$, the corresponding resultant force $F'_x$ can be written as:

$$F'_x = -n \frac{e^2}{4\pi \varepsilon_0} \sum_{i=1}^{4} \frac{\delta + (i + 2)a}{[(a/2)^2 + \delta + (i + 2)a]^{3/2}}. \quad (8)$$

Now we can obtain a general formula of the total force $F_{\text{total}}$ applied to the electron $A$

$$F_{\text{total}} = f_B + F_x + F'_x. \quad (9)$$

Figure 5 shows the relationship between total confinement force $F_{\text{total}}$ and $\delta/a$ for different $l$ with the special condition $Q = +e$ (or $n = 1$). Fig. (b) is the enlarged figure of the rectangular area of Fig. (a).

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Figure 5 shows the relationship between total confinement force $F_{\text{total}}$ and $\delta/a$ for different $l$ with the special condition $Q = +e$ (or $n = 1$). From the Fig. 5(a), it can be seen clearly that there are two main regions where the right region indicates the repulsive interaction between electron $A$ and $B$, while the left region indicates the attractive interaction between two electrons. Furthermore, for a given $l$, as better shown in the enlarged Fig. 5(b) that there exists a special position $\lambda_l$ (the deviation of the electron from its initial equilibrium position $a/2$) at
where \( \lambda \) can be quantitatively described as the following equation:

\[
\lambda = \frac{a^2}{\xi^2}
\]

as shown in Fig. 6. The relationship between them should develop their self-organized at the corresponding equilibrium positions (\( \xi_\ell/a \)).

The result implies that the force (the deviation of the electron from its initial equilibrium position \( a/\xi \)) inside the superconducting phase because of the interaction among the vortex lines. This energy may directly influence the stability of the superconducting vortex lattice, the superconducting electrons obtain the will decrease respectively.

Moreover, according to the numerical results, we can obtain the \( \lambda_\ell \) as a function \( \xi_\ell/a \) (where \( \xi_\ell \) is the spacing of the electron A and B) for electron A with \( l \) from 1 to 10, as shown in Fig. 6. The relationship between them can be quantitatively described as the following equation:

\[
\lambda = \frac{a^2}{\xi^2}, \quad \text{as illustrated in the blue line in Fig. 6}
\]

In our theoretical framework, for a stable superconducting vortex lattice, the superconducting electrons should develop their self-organized at the corresponding equilibrium positions (\( \lambda_\ell = 0 \)) due to competition between the stripes. This result implies that the formation of an ordered superconducting vortex lattice is always accompanied by the existence of electromagnetic energy (\( E_c \)) inside the superconducting phase because of the interaction among the vortex lines. This energy may directly influence the stability of the superconducting vortex lattice and the corresponding superconducting transition temperature of the superconductor. In the following, we will discuss qualitatively which factors might influence the energy \( E_c \).

We know that the interaction energy between two electrons spaced \( \xi \) apart can be presented by

\[
E_c \propto \frac{1}{\xi^2}. \quad (10)
\]

Suppose the distance between two electrons decreases by \( \Delta \xi \), then the interaction energy \( E_c \) will increase by

\[
\Delta E_c \sim \frac{1}{\xi^2} \Delta \xi. \quad (11)
\]

From Eq. (11), it is not difficult to find that the \( \nabla E_c \) can be effectively reduced by increasing \( \xi \) or by decreasing \( \Delta \xi \). In fact, the physical essence of \( E_c \) can root to the energy of \( \Delta E_c \). Physically, we argue that the parameter \( \lambda \) of Fig. 6 is closely related to the \( \Delta \xi \) of Eq. (12), for convenience, we assume that they are linearly related by \( \lambda \sim \Delta \xi \). Then according to the above relation (\( \lambda = 1/\xi^2 \)) and Eq. (12), the energy \( E_c \) can be simply expressed as:

\[
E_c \sim \frac{1}{\xi^2} \Delta \xi \sim \frac{1}{\xi^2} \lambda \sim \frac{1}{\xi^4}. \quad (12)
\]

This equation tells us that in order to obtain a more stable superconducting vortex lattice with a higher temperature, the stripe-stripe spacing should be sufficiently increased. A more detailed discussion will be given in the next section.

IV. THE EFFECTIVE C-AXIS LATTICE CONSTANT AND THE SUPERCONDUCTING CRITICAL TEMPERATURE

Based on the above discussions, we will further explore how to enhance the superconducting transition temperature of the layered superconductors. In our scenario, a higher \( T_c \) means a smaller energy \( E_c \), consequently, a larger \( \xi \) according to Eq. (12). It was pointed out in the previous section, for the doped layered superconducting materials, there are two ways (the carrier concentration and the c-axis lattice constant) to adjust the stripe-stripe spacing.
conductors. We argue that the possible maximum $T_c$ constant and the newly defined parameter of effective c-axis lattice constant vary considerably among the superconductors, as shown in Table I and Fig. 7. $T_c$ transition temperatures with the increasing of the effective c-axis lattice constant. Importantly, although the crystal structure and physical properties of the superconducting planes inside a unit cell of the superconductors, our theory suggests that the changing of the carrier concentration can only modestly increase $T_c$, while the increasing of the effective c-axis lattice constant can lead to a significant enhancement of $T_c$ of the superconducting materials. This argument has been well confirmed by numerous experimental investigations in the cuprate and iron pnictide superconductors, as shown in Table I and Fig. 7.

Table I shows the experimental data of the c-axis lattice constant $c^*$ for the layered cuprate and iron pnictide superconductors. We argue that the possible maximum $T_c^{max}$ for SmO$_{1-x}$Fe$_x$As of 55 K (1111 series), (Sr$_2$V$_2$O$_6$)Fe$_2$As$_2$ of 46 K (21311 series) and Ba$_{1-x}$K$_x$Fe$_2$As$_2$ of 38 K (122 series) cannot exceed 60 K, 50 K and 40 K, as indicated by three cyan lines in the figure.

To obtain the analytical relationship between the $T_c^{max}$ and $c^*$, the experimental results of Table I are represented in Fig. 4. Surprisingly, except for the last two samples (Tl$_2$Ca$_2$Ba$_2$Cu$_2$O$_{10}$ and Hg$_2$Ba$_2$Ca$_2$Cu$_2$O$_{10}$), the figure shows clearly that all of the experimental data almost fall on a same straight line which can be described with the equation:

$$T_c^{max} = 10c^* - 28.$$

(13)

It should be emphasized that the Eq. (13) proposed here has its scope of application since our superconducting mechanism requires an effective competition among electrons and stripes, too intensive (for a small $c^*$) or too weak (for a large $c^*$) competition is not conducive to the formation of superconducting vortex lattice. It is estimated from Eq. (13) that when $c^*$ is less than 2.8Å, the corresponding layered materials cannot exhibit the superconductivity. Of course, there must be a maximum value of $c_{max}^*$ which also led to the failure of the establishment of the superconducting vortex lattice inside the materials. We note from the figure that, as unexpected, the superconducting transition temperatures of Tl$_2$Ca$_2$Ba$_2$Cu$_2$O$_{10}$ and Hg$_2$Ba$_2$Ca$_2$Cu$_2$O$_{10}$ deviate seriously from the linear equation of Eq. (13). We think that there may be two reasons for these deviations. First, since the carrier concentrations of these two superconductors are unadjustable, it is likely that the vortex lattices are not in best consistent with those of the crystal structures. Second, their effective c-axis lattice constants have been very close to the maximum value of $c_{max}^*$. Personally, we believe that the maximum $T_c^{max}$ of the cuprate superconductors may be raised to the theoretical value (about 161 K, as marked in Fig. 7) without applying of the external pressure. Then, can we predict the limits of the $T_c^{max}$ according to our theory? From the viewpoint of lattice stability and competition among superconducting electrons, a maximum value of $c_{max}^*$ values range from 19Å (the $c^*$ of Hg$_2$Ba$_2$Ca$_2$Cu$_2$O$_{10}$) to 19-3Å (where 3Å is about the thickness of two atomic layers). Hence by Eq. (13), we conclude that the limits of the $T_c^{max}$ (~192K) is very difficult to break through 200 K in three-dimensional bulk superconductors.

As is well known, soon after the discovery of the iron-based superconductors, some physicists have believed room temperature superconductivity may be possible in these new compounds. We think that these predictions are apparently lack of solid scientific basis. As can be found from Table I and Fig. 7 the experimental data of three iron-based superconductors: SmO$_{1-x}$Fe$_x$As of 55 K (1111 series) Ba$_{1-x}$K$_x$Fe$_2$As$_2$ of 38 K (122 series) and (Sr$_2$V$_2$O$_6$)Fe$_2$As$_2$ of 46 K (21311 series). According to the theory suggested in this paper, we argue that the possible maximum $T_c^{max}$ for 1111, 122 and 21311 series cannot exceed 60 K, 40 K and 50 K, as indicated in Fig. 7 (three cyan lines).

Furthermore, we will show that our theory can provide a qualitative explanation of why the superconduc-
tivity does not occur in noble metals (for example, Ag, Au, and Cu) and a also new insights into the problem of the superconductivity in metallic hydrogen. It is a common knowledge that gold, silver and copper are the best conductors of electrical current. However, a question has long plagued the physics community: why an ideal conductor that is not a superconductor? With the help of the Fig. 2 and Eq. (13), we try to unravel this mystery in a very simple way. Under normal circumstances, good conductors always have an extremely high level of carrier concentration. One can assume that these metals have the superconducting properties, in our view, it is necessary that the superconducting electrons should be arranged as the specific vortex lattices of Fig. 2 with the stripe-stripe spacing inside the superconducting CuO planes is far less than 2.8Å.

Physicists predicted that hydrogen in solid-state can be a high-temperature superconductor, and maybe even a room-temperature superconductor. Indeed, this prediction sounds very interesting and attractive, but we would like to point out that it cannot be realized as desired. From the perspective of atomic structure, there are the same number of carriers (free electrons) in metallic hydrogen, lithium (BCC, \(a = b = c = 3.51\) Å), sodium (BCC, \(a = b = c = 4.29\) Å) and potassium (BCC, \(a = b = c = 5.33\) Å) with the same number of atoms. The theoretical predicted lattice constants of metallic hydrogen (BCC, \(a = b = c = 2.89\) Å) are smaller than those of the other three materials, indicating that metallic hydrogen has the highest carrier concentration among them. As lithium, sodium and potassium do not exhibit superconductivity, now we can boldly predict that the metallic hydrogen with the highest carrier concentration cannot be a superconductor at any low temperature, not to mention the room temperature superconductivity.

Finally, it is worth to note that the suggested real-space effective c-axis lattice constant theory of superconductivity has been excellently confirmed by recent measurements\[^{18}\]. Fig. 8(a) shows a unit-cell of cuprate \(La_{2-x}Ba_xCuO_4\) of 40 K with the c-axis lattice constant \(c = 13.23\) Å. It is easy to find from the figure that superconducting layer (CuO plane) spacing (the effective c-axis lattice constant) of the superconductor is \(c^* = c/2 = 6.615\) Å. If there are experimental methods that can cause one of the CuO plane to lose the ability of conducting superconducting current, then the effective c-axis lattice constant can be promoted to \(c^* = c = 13.23\) Å, consequently, the corresponding maximum \(T^c_{c,max}\) may be dramatically enhanced to 104 K calculated according to Eq. (13). This prediction has just been experimentally verified by Gao et al.\[^{18}\] in cuprate \(Sr_{2-\delta}Ba_{\delta}CuO_{3+\delta}\), which look very similar to that of \(La_{2-x}Ba_xCuO_4\) but with partially occupied apical oxygen sites, as shown in Fig. 8(b). Why can two almost the same superconducting materials have completely different superconducting transition temperatures? Although several factors have been considered in what enhance the transition temperature, it is intuitively obvious that the actual reason has not been elucidated yet. In our theoretical framework of the effective c-axis lattice constant, it is most likely that the introducing of partially occupied apical oxygen sites could cause one of the CuO layers no longer to function as the superconducting plane. Therefore, the two analogous superconductors of Fig. 8 have completely different relation between \(c\) and \(c^*\): \(c^* = c/2\) for \(La_{2-x}Ba_xCuO_4\) of Fig. 8(a), while \(c^* = c\) for \(Sr_{2-\delta}Ba_{\delta}CuO_{3+\delta}\) of Fig. 8(b). From the experimental results of \(Sr_{2-\delta}Ba_{\delta}CuO_{3+\delta}\) (\(c^* = c = 12.78\) Å) and Eq. (13), one can get immediately \(T^c_{c,max} \approx 99.8\) K which is in good agreement with the experimental result \((T^c_{c} \approx 98\) K)\[^{18}\].

V. CONCLUDING REMARKS

We have proposed the real-space effective c-axis lattice constant theory of superconductivity based on the self-organized picture of the superconducting electrons and studied the stability of the superconducting vortex lattices in layered superconductors. It has been shown
clearly that the effective lattice constant play a significant role in promoting the superconducting transition temperature in layered superconductors, such as the copper-based and newly discovered iron-based compounds. According to a large number of experimental data, we have obtained an important equation: $T_{c}^{\max} = 10c^* - 28$ which can be used to estimate the highest possible $T_{c}^{\max}$ for a given layered superconductor, where $c^*$ is the effective c-axis lattice constant. This result suggests that the maximum possible $T_{c}^{\max}$ of the iron-based superconductors cannot exceed 60 K, 50 K and 40 K for the 1111, 21311 and 122 series, respectively. It should be noted that this prediction has stood the test of time for about two years by many experiments. Furthermore, we have tried to explain why two very similar cuprate superconductors ($\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ of 40 K and $\text{Sr}_{2-x}\text{Ba}_x\text{CuO}_{3+x}$ of 98 K) would have such a different superconducting transition temperatures, the latter is about 2.5 times of the former. The physical reason why the superconductivity does not occur in gold, silver and copper has also been provided based on the suggested new mechanism. Finally, we have argued that the metallic hydrogen cannot exhibit superconductivity at any low temperature. We think that the real-space effective c-axis lattice constant theory of superconductivity may finally shed light on the mysteries of superconductivity. With these results, the scientists will be able to proceed to the materials design for the new superconductors that may have a higher superconducting transition temperature.

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