The Mystery of Superconductivity: Glue or No Glue?

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In this study, a possible non-quasiparticle glue for superconductivity of both conventional and unconventional superconductors is explored in a pure electron picture. It is shown clearly that the moving electrons due to the electromagnetic interaction can self-organize into some quasi-one-dimensional real-space charge stripes, which can further form some thermodynamically stable vortex lattices with trigonal or tetragonal symmetry. The relationships among the charge stripes, the Cooper pairs and the Peierls phase transition are discussed. The suggested mechanism (glue) of the superconductivity may be valid for the one- and two-dimensional superconductors. We also argue that the highest critical temperature of the doped superconductors is most likely to be achieved around the Mott metal-insulator transition.

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I. INTRODUCTION

Since the discovery of superconductivity in mercury by K. Onnes in 1911 [1], great efforts have been made to finding out how and why it works. It has been widely accepted that the BCS (Bardeen-Cooper-Schrieffer) [2] successfully explained the superconducting behavior in conventional superconductors by predicting that the electrons near the Fermi surface can be ‘glued’ together in Cooper pairs by the attractive force of the electron-phonon interaction. According to the microscopic BCS theory, the maximum critical temperature ($T_c$) of superconductors cannot exceed the McMillan limit of 39 K.

With the discovery of a family of cuprate-perovskite ceramic materials known as high-temperature superconductors in 1986 [3, 4], many theoretical condensed matter physicists have started to doubt the reliability of the phonon-mediated BCS theory [5]. As we know that the highest critical temperature of cuprate superconductors ever recorded is $HgBa_2Ca_2Cu_3O_8$ (under 30 GPa pressure) [6], which has a critical temperature as high as 164 K. This indicates that the gentle lattice vibrations (phonon-glue) may be not the right candidate for high-temperature superconductivity. Recently, the reliability of BCS theory has been further challenged by the new iron arsenide superconductors with critical temperatures in excess of 50 Kelvin [7, 8]. In fact, at high temperatures, the vibration becomes so vigorous that it tends to break up the electron pairs instead of binding them together [9]. So what could possibly provide the “glue” for high temperature superconductivity?

As is well known, twenty-three years after the appearance of the high-temperature superconductors, though more than 100,000 papers on the materials have been published and many “glues” (for example, the magnetic resonance mode, spin excitations and phonons) have been suggested, however, scientists have been still debating the underlying physical mechanism for this exotic phenomenon. Theorists have created a large number of theoretical models for high-transition-temperature, as a result, it makes the problem even more confusing. Just as Steven Kivelson said, “The theoretical problem is so hard that there isn’t an obvious criterion for right” [10]. In a recent paper, Anderson even questioned the existence of any electron-pairing glues in cuprate superconductors [4]. More recently, Pasupathy et al. [11] showed temperature-dependent scanning tunneling spectroscopy data which has been believed to be strong evidence for the “no glue” superconducting picture.

It is now quite clear that superconductivity can occur in a wide variety of materials, including some simple elements (like niobium and tantalum), various metallic alloys and organic materials. Thus, it is not surprised to find that more and more materials with the superconducting properties will be discovered in future. Most theorists believe that new superconductors always reveal the need for fresh mechanism and theoretical models. Moreover, they hope to uncover the mystery of superconductivity simply through the Hamiltonian, which has been discussed ad nauseum by now. But our viewpoint is somewhat different from the these physicists. In our opinion, if there exists only a few materials with the superconductivity, it may be reasonable to expect that they have different superconducting mechanisms. As so many materials with superconductivity have been discovered, it becomes more clear that the all superconducting phenomena should share an exactly the same physical reason. Furthermore, the new mechanism for the electron-pairing glue that gives rise to superconductivity should not be established in Hamiltonian systems.

In this paper, we will present a non-quasiparticle “glue” which can naturally bring the moving electrons together and condense them into some real-space superconducting vortex lattice states.

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II. CAN ELECTRONS ATTRACT EACH OTHER?

In spite of more than twenty years of long and difficult debates on what causes high-temperature superconductivity, we insist that there might just be a single and simple explanation for electron coupling in various superconductors. Superconductivity, as a widespread natural phenomenon should be governed by a unique and fundamental deterministic law of nature.

Normally, electrons repel each other according to Coulomb’s law, they are attracted only to protons or positive ions. However, it is argued that electrons should attract each other in some particular situations like superconductivity. Do electrons attract electrons?

As shown in Fig. 1 we have a new window on this critical question of what holds electrons together. According to electromagnetic theory, an electric current produces a magnetic field which will exert force on the mobile electrons nearby, as illustrated in Fig. 1(a). It is a common knowledge that it is the directional movement of electrons which are responsible for electric current in conductors such as wires, as shown in Fig. 1(b). This figure implies a very important message that the electrons moving in the same direction may mutually attract, rather than mutually repel in their resting state. It seems likely that this fundamental physical fact or property has been overlooked by the researchers of condensed matter physics. This scenarios of Fig. 1(b) provides a natural glue (without the concept of quasiparticle) which can bring the moving electrons together, a more detailed discussion will be given in next section.

III. THE ELECTROMAGNETIC INTERACTION INDUCED SELF-ORGANIZATION OF MOVING ELECTRONS

From the view of crystallography, all superconducting materials can be simply depicted in Fig. 2, which contains two basic elements: (1) the lattice structure of positive charge (ions), and the carriers of negative charge (electrons). Here, we may raise one most essential question: what is the fundamental difference between the superconducting materials and the non-superconducting materials? The answer is simple and definite: to be a superconductor, the materials should include an appropriate carrier number, or with an appropriate carrier concentration (not too high, not too low). Of course, in order to obtain a higher superconducting temperature, we will show that some matching conditions between the carrier concentration and the lattice structure should be naturally satisfied.

It is well known that the application of an external electric field (in $-y$ direction) on a material can cause an overall movement of the charge carriers (electrons) in $y$ direction, see Fig. 3(a). Under the conditions of low temperature and low carrier concentration, it seems likely that new physical phenomena will emerge, as shown in Figs. 3(b)-(d). As time goes by, the electrons of the directional movement will gradually gather together and self-organize into some highly ordered charge structures due to the magnetic field forces as illustrated From Fig. 3(b) to Fig. 3(d). Finally, these moving electrons will condensed into some quasi-one-dimensional charge stripes (vortex lines), or “charge rivers” [12, 13]. In this case, the corresponding superconductor exhibits a peculiar form of real-space phase separation, these “charge rivers” are formed spontaneously and segregated by the domain walls of the positive ions, as shown in Figs. 3(d). Based on the energy minimization principle, to be a sta-
FIG. 3: The external electric field induced self-organization of the charge carriers. (a) An overall movement of the electrons in $y$-direction, (b) the appearance of the blurred charge rivers, (c) more electrons join the charge rivers, (d) the moving electrons are finally condensed into some quasi-one-dimensional charge stripes (or superconducting vortex lines) separated by the domain wall of the positive ions.

FIG. 4: To achieve the highest superconducting transition temperature, the superconducting vortex lattices should be in the following four stable structures, (a) and (b) the vortex lattices with tetragonal symmetry, while (c) and (d) having the trigonal symmetry.

IV. PEIERLS PHASE TRANSITION AND COOPER PAIRS

In the framework of the self-organized of the moving electrons and the vortex lattices of Fig. 4 what factors can affect the superconducting transition temperature? Figure 5 shows an area of superconducting plane, where $\xi$ is the stripe-stripe separation, $d$ is the width of domain-wall, $a$ and $b$ are the lattice constants, and $\delta$ is the electron-electron distance within one vortex line. In general, all of these structure parameters can influence the critical temperature of the corresponding superconductor. Qualitatively, for a relatively wide domain-wall...
The stability of the charge river and a higher $T_c$ Peierls chain with the electron-electron separations $\delta$ is enhanced in the superconductors with a small lattice constant $b$. A periodic vortex line may survive in the superconductors with a small lattice constant $b$. The superconducting vortex lines are most likely in a Peierls chain with the electron-electron separations $\delta$ and $b-\delta$; in this special case, the Cooper pairs can naturally form inside each plaquette alone the vortex lines. An unstable vortex line that may be easily destroyed by the strong electron-electron interactions among the crowded electrons (or a larger stripe-stripe separation), the stripe-stripe interactions will be greatly reduced, and consequently enhance the stability of the superconducting state which in turn improve the superconducting transition temperature of the superconductor. Hence, the high-temperature superconducting materials typically have a very low carrier concentration (for example, the cuprate superconductors), while the conventional superconductors have a relatively high carrier concentration. Moreover, the materials with an exceptionally high carrier concentration (the electrons are too crowded to form the order stripes) may not be superconductors at any low temperatures, such as gold, silver and copper, the most common good conductors of electricity. To maintain a more stable charge river (vortex line), the mobile electrons must be effectively confined in some quasi-one-dimensional spaces (say the cyan lines in Fig. 5), usually, a small lattice constant $a$ and a thick domain wall $d$ are conducive to the stability of the charge river and a higher $T_c$ superconducting state.

As an approximate description, we use a single parameter $\delta$ to characterize a superconducting vortex line in Fig. 5. It should be pointed out that the formation of charge stripe is generally attributed to the competition between the short-range electron-electron static electric repulsion and the long-range dynamic magnetic attraction of Fig. 1(b). Consequently, there exists an optimal electron-electron separation within the vortex line. We will discuss in next paper that, to be a superconducting vortex line, the corresponding electron-electron separation should lay in the range of $1.4 \sim 1.8 \AA$. In addition, we must emphasize that the one parameter’s description (see Fig. 5) of the vortex line is not accurate, for a real superconductor, the electron-electron distance inside one vortex line is modulated by lattice structure of the superconductor.

Further, we consider the effects of the lattice structure of the superconductor on the formation of the one-dimensional vortex lines. As shown in Fig. 6, the vortex lines in the quasi-static state may have different structures. Fig. 6(a) shows a periodic vortex line with the electron-electron separation $\delta$ equals to the lattice constant $b$, in the case of small lattice constant, such vortex lines may exhibit the superconductivity phenomenon. This may be considered as a non-pairing mechanism of superconductivity. However, for a large lattice constant $b$, the moving vortex lines will be very unstable due to a rather weak magnetic attraction depicted in Fig. 1. For most materials, the lattice constant $b$ usually ranges between 3$\AA$ to 4$\AA$, which is about two times as large as the optimal electron-electron separation (\(~\sim\) 1.5$\AA$). This implies that there are (average) two electrons (Cooper pair) inside one plaquette along one superconducting vortex line, as shown in Fig. 6(b) which can be considered as the lattice structure induced Peierls phase transition. If there are more than three electrons inside one plaquette [see Fig. 6(c)], the electrons are too crowded inside the vortex lines and the electron-electron static electric repulsions are strong enough to break up the vortex lines.

In the following, we will focus our attention on the formation of the Cooper pair in Fig. 4(b). Along one superconducting vortex line, the electrons are dimerized into Cooper pairs with a spacing of $\delta$, as shown in Fig. 4. So the electrons moving inside the vortex lines are in the energy minimum Peierls chains. For the purpose of a simplified case, we consider only the nearest-neighbor electron-electron and ion-electron interactions. Based on Figure 4(c), the nearest-neighbor electron-electron interactions on electron A can be expressed as:

$$f_B = \frac{e^2}{4\pi \varepsilon_0 R^2},$$

$$f_{B'} = \frac{e^2}{4\pi \varepsilon_0 (b - \delta)^2}.$$

FIG. 6: (a) Non-pairing superconducting vortex line may survive in the superconductors with a small lattice constant $b$. (b) The superconducting vortex lines are most likely in a Peierls chain with the electron-electron separations $\delta$ and $b-\delta$; in this special case, the Cooper pairs can naturally form inside each plaquette alone the vortex lines. (c) An unstable vortex line that may be easily destroyed by the strong electron-electron interactions among the crowded electrons.

FIG. 7: A picture of detailed illustration of electron-electron and ion-electron interactions inside a vortex line.
Under the special conditions of $a = b$ and $Q = e$, a quasi-static Cooper pair may exist in the plaquette with an electron-electron separation $\delta = 0.525b$.

If for each lattice ion carrying a positive charge $Q$, we can get the nearest-neighbor ion-electron interactions on electron A as

$$f_1 + f_2 = \frac{2Qe(b - \delta)}{\pi \varepsilon_0 [a^2 + (b - \delta)^2]^{3/2}}, \quad (3)$$

and

$$f_3 + f_4 = -\frac{2Qe(b + \delta)}{\pi \varepsilon_0 [a^2 + (b + \delta)^2]^{3/2}}. \quad (4)$$

Now we have a general formula of the total confinement force $F$ applied to the electron A (or B) of the Cooper pair as

$$F = f_B + f_{B'} + f_1 + f_2 + f_3 + f_4. \quad (5)$$

Physically, when $F$ is equal to zero, it indicates a completely suppression of the Coulomb repulsion between two electrons. As a consequence, the electrons will be in the energy minimum bound state. Based on the analytical expressions (1) – (4), we draw in Fig. 8 the confinement force $F$ versus $\delta/b$ under the conditions $Q = e$ (or $n = 1$) and $a = b$. This figure reveals one important fact: the combination of the ion-electron and electron-electron interactions can lead to the well-known Peierls phase in the superconducting vortex lines, where there are two electron-electron separations of $\delta_1 = \delta = 0.525b$ and $\delta_2 = b - \delta = 0.475b$.

V. CONCLUDING REMARKS

We have proposed the self-organized picture of vortex lines due to the electromagnetic interaction of the mobility electrons. It has been shown clearly that the electrons moving in the same direction may mutually attract, rather than mutually repel in their resting state. In our approach, the microscopic scenario for the superconductivity can be considered as a "no glue" superconducting picture because no any quasiparticles are involved in the suggested mechanism. This no quasiparticle characteristic implies that the proposed scheme represents an unified interpretation of the superconductivity phenomena of any kind of superconductors. We think that the suggested real space self-organized mechanism of the charge carrier may finally shed light on the mysteries of superconductivity. Furthermore, our researches also reveal that the Peierls phase transition is induced by the ion-electron interactions, rather than spontaneous generation. We have argued that the highest $T_c$ of the doped superconductors may be achieved around the Mott metal-insulator transition, where the suggested real-space superconducting vortex lattice is in its minimum energy state.

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