Intrinsic correlation between superconductivity and magnetism

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Based on the real-space Mott insulator model, we establish a unified pairing, coherent and condensate mechanism of superconductivity. Motivated by Dirac's magnetic monopole and Maxwell's displacement current hypothesis, we demonstrate that electric and magnetic fields are intrinsically relevant. An isolated proton or electron creates an electric field, whereas a quantized proton-electron pair creates a magnetic field. The electric dipole vector of the proton-electron pair is the Ginzburg-Landau order parameter in the superconducting phase transition. The Pierce-like dimerization pairing transition of the electron-proton electric dipole lattice leads to the symmetry breaking of the Mott insulating state and the emergence of superconducting and magnetic states. This theoretical framework can comprehensively explain all superconducting phenomena. Our research sheds new light on electron spin, magnetic monopoles, and the symmetry of Maxwell's equations.

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The superconductivity research boom began with Bednorz and Müller's discovery [1]. Microscopic theories and models, including RVB [2], Hubbard models [3], gauge theory [4], spin singlet [5], and d-wave pairing [6], have been proposed following Cooper's pairing model [7]. However, these theories cannot fully explain all experimental results [8]. Superconducting materials exhibit zero resistance in an electric field [9] and the Meissner effect in a magnetic field [10]. Both are related to the magnetic field, described by Ampere's law. Therefore, understanding magnetism is crucial for explaining superconductivity.

It is widely recognized that existing theories and models of superconductivity are based on the Drude free electron model, which relies on moving electrons to explain current and magnetic fields. We propose a unified microscopic mechanism based on Mott insulators with localized electrons [11], where current and magnetic fields are attributed to Maxwell displacement current and Dirac magnetic monopoles rather than electron motion.

Our proposal traces natural magnetic phenomena to the simplest electron-proton pair, where the pairing generates a magnetic field and individual electrons or protons generate an electric field. The proton-electron electric dipole vector is the Ginzburg-Landau order parameter for the superconducting phase transition [12]. The mechanism explains many superconducting phenomena and encompasses the symmetry of Maxwell's equations [13], electron spin [14], and Dirac's magnetic monopoles [15].

The duality between electric and magnetic fields is a fundamental concept in electromagnetism, which implies that generating a magnetic field requires static magnetic charges, as Dirac proposed in the theory of magnetic monopoles. It was suggested that electric and magnetic charges could coexist and satisfy the following quantization condition:

$$eg = \frac{hc}{4\pi}n = \frac{\hbar c}{2}n, \quad (1)$$

where e and g are the electric and magnetic charges, respectively, h is the Plank's constant, and n being the integers.

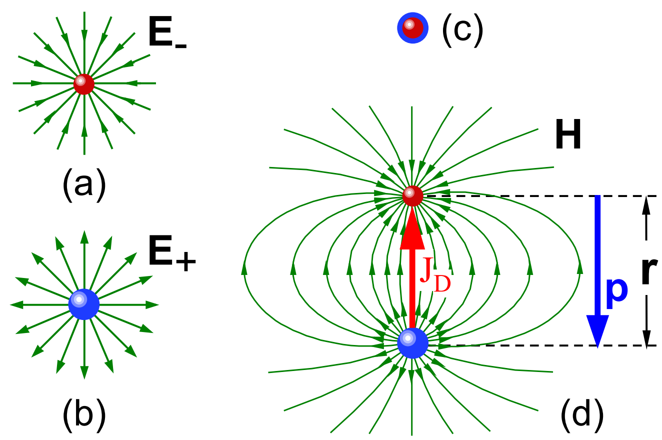

FIG. 1. Relationship between electrostatic field and static magnetic field. (a) and (b) Isolated charges produce electric fields; (c) due to the symmetry, the electromagnetic field is hidden; (d) when the symmetry is broken, a magnetic field is excited.

The seemingly simple formula (1) hides the secret of the origin of the magnetism of materials. Using the fine structure constant $\alpha = e^2/4\pi\varepsilon_0\hbar c$, the Eq. (1) can be re-expressed as:

$$g = (\frac{n}{8\pi\varepsilon_0\alpha})e = \Pi_n e, \quad (2)$$

where Π_n is an adjustable constant.

The relationship presented in Eq. (2) above provides a clear understanding that the purported magnetic monopoles are, in fact, just dressed electrons or protons. This means that the superimposed electric field created by the electron-proton pair is the magnetic field. Intriguingly, electrons and protons can simultaneously act as electric and magnetic charges. In the subsequent sections, we will reconfirm this conclusion in accordance with Maxwell's theory.

Figs. 1(a) and (b) show isolated electron or proton generating electric fields $\mathbf{E}_-$ and $\mathbf{E}_+$ respectively. As in Fig. 1(c), no electromagnetic field exists when coinciding. In Fig. 1(d), a separation of $\mathbf{r}$ forms an electric dipole through symmetry breaking, and a magnetic field emerges. It is well-known that a proton-electron pair can form a hydrogen atom or a neutron, and it is worth emphasizing that the proton-electron pair is the smallest quantized capacitance in nature. According to Maxwell's theory, a displacement current density $\mathbf{J}_D = \varepsilon_0 \partial \mathbf{E}/\partial t$ exists in the capacitor, which will create an associated magnetic field in the surrounding space. As Maxwell's statement suggests, a changing electric field produces a magnetic field, which is given by $\mathbf{H}$ as follows:

$$\mathbf{B} = \mu_0 \mathbf{H} = \frac{\mathbf{E}_+ + \mathbf{E}_-}{c}, \tag{3}$$

where c is the speed of light and μ_0 is the vacuum permeability.

The formula shows that an isolated electron generates only an electric field and lacks spin properties. Modern physics proposes electron spin based on atomic fine spectral structure [16] and Stern-Gerlach silver atomic beam experiment [17]. However, these experiments only show magnetic moments in atoms such as silver or hydrogen (electron-proton pairs), not free electrons. We have unified particles such as hydrogen atoms, neutrons, electric dipoles, quantized capacitors, and magnetic monopoles as paired composites of electrons and protons. Physical quantities such as spin, magnetic moment, displacement current, and magnetic field are unified as electric dipole electric fields.

Maxwell's equations are elegant but not invariant under duality transformation. Is the asymmetry between electric and magnetic fields a reflection of nature or our interpretation? We will provide a clear answer. The Maxwell's first equation $\nabla \cdot \mathbf{E} = \rho_e/\varepsilon_0$ and the second equation $\nabla \cdot \mathbf{B} = 0$ are completely independent of each other, so strictly speaking, the electromagnetic field is not unified. Here, we will show that the second equation can be derived from the first. For a proton-electron pair with an electric dipole vector of $\mathbf{p}$, substituting the electric fields excited by the electron and proton into Eq. (3) yields:

$$\nabla \cdot \mathbf{B} = \frac{[\rho_e(\mathbf{r}_p) + \rho_{-e}(\mathbf{r}_p + \mathbf{p}/e)]}{c\varepsilon_0}. \tag{4}$$

Under a far-field approximation $\mathbf{r}_{\mathrm{p}} >> \mathbf{p}/e$, then $\rho_e(\mathbf{r}_p) + \rho_{-e}(\mathbf{r}_p + \mathbf{p}/e) \simeq 0$, this result means that the right-hand side of the second Maxwell's equation is not exactly zero. Furthermore, our assumption has ruled out the presence of the conduction current ($\mathbf{J}_e = 0$). Thus far, we can now present the corrected Maxwell's equations:

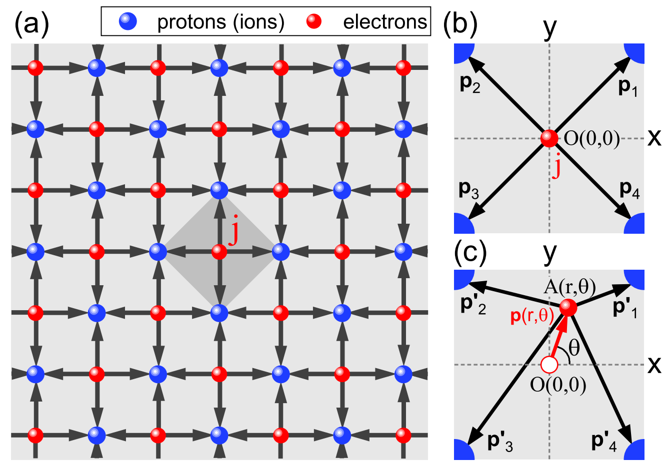

FIG. 2. (a) The electric dipole vector represents 2D Mott insulator with the intrinsic antiferromagnetic long-range order, (b) a electron in ground state; (c) the electron in excited state.

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= \frac{\rho_e}{\varepsilon_0}, \\
\nabla \cdot \mathbf{B} &\simeq 0, \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}, \\
\nabla \times \mathbf{B} &= \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}.
\end{aligned} \tag{5}$$

Eq. (5) has two breakthroughs: (1) the new first and second equations are linked, describing electric and magnetic fields respectively, and (2) the absence of conduction current leads to symmetry in the third and fourth equations. Based on the first and second of Eq. (5), a crystal composed of electron-proton (ion) pairs can be viewed as a super large-scale integrated capacitor. The current is interpreted as an electromagnetic wave with the third and fourth equations. As a result, research on avoiding collisions between electrons and the lattice in superconductivity has been transformed into an investigation into reducing the loss of electromagnetic waves during propagation within wires.

Fig. 2(a) shows a Mott insulator decorated with electric dipole vectors, possessing inherent antiferromagnetic long-range order. Fig. 2(b) is the unit cell, where four degenerate electric dipole vectors ($\mathbf{p}_1$, $\mathbf{p}_2$, $\mathbf{p}_3$, and $\mathbf{p}_4$) can be integrated into a total vector $\mathbf{P}_{\mathrm{O}} = 0$ due to symmetry. As shown in Fig. 2(c), external factors (temperature, pressure, and electromagnetic fields) can cause the ground state electron to enter an excited state $A(r, \theta)$ with a vector $\mathbf{p}(r, \theta) = e\mathbf{r}$. The sum of four electric dipole vectors ($\mathbf{p'}_1$, $\mathbf{p'}_2$, $\mathbf{p'}_3$, and $\mathbf{p'}_4$) is expressed as $\mathbf{P}_{\mathrm{A}} = -\mathbf{p}(r, \theta) = -er\exp(i\theta)$. The emergence of the vector $\mathbf{P}_A$ indicates the excitation of a hidden magnetic state in the superconducting parent, leading to the destruction of the Mott antiferromagnetic phase. Moreover, the vector can function as the spin and magnetic moment of the excited electrons. Notably, the Electron's magnetism or spin

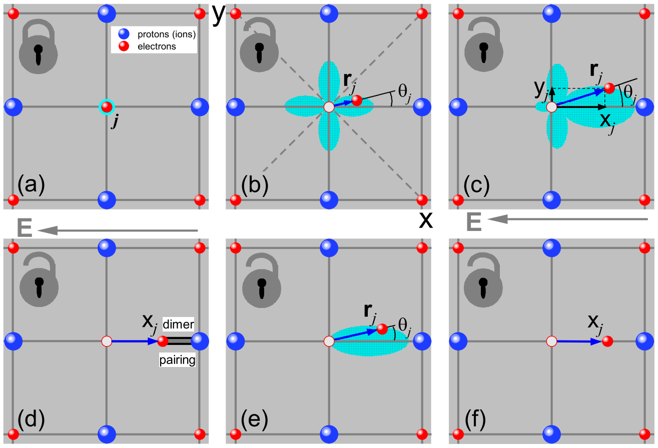

FIG. 3. Five condensed states based on symmetry and symmetry breaking under nearest-neighbor and next-neighbor interaction: (a) insulating state; (b) normal state with d-wave symmetry; (c) externally-induced metallic state; (d) superconducting state; (e) and (f) unsaturated and saturated magnetic states.

arises from a combination with positively charged lattices, disappearing upon departing material and becoming free. Electrons do not have intrinsic spin, explaining the observed charge-spin separation in experiments [18].

The Ginzburg-Landau theory is the most successful theory of superconductivity, capturing the order parameter and symmetry breaking of superconducting phase transition. However, it cannot address the microscopic question of what constitutes the order parameter with electromagnetic properties. Our theory can answer this question. For a conductor with N valence electrons, by using $\mathbf{P}_A$, the order parameter can be defined as:

$$\mathbf{P}_{order} = \sum_{j=1}^{N} e r_j \exp(i\theta_j) \tag{6}$$

By using Eq. (6), it is possible to distinguish among five typical condensed states and display their essential differences at the microscopic scale. First, as shown in the Fig. 3(a), for any valence electron in the material (marked with j), because $r_j = 0$, then the order parameter $\mathbf{P}_{order} = 0$, this is the insulating state in which no symmetry breaking occurs. In the second scenario depicted Fig. 3(b), the random thermal fluctuations combine with Coulomb attraction in the x and y-directions and Coulomb repulsion in the two diagonal directions, resulting in the formation of the d-wave pairing symmetry. Because its rotational symmetry, $\mathbf{P}_{order} = 0$. Fig. 3(c) represents the metallic state. The combined action of the electric field and random thermal motion makes the dominant component of the order parameter appears in the x-direction, displacement x_j contributes current and y_j produces resistance. Fig. 3(d) depicts the superconducting state where thermal disturbance is completely suppressed, which arises from a Pierce-like dimerization pairing transition

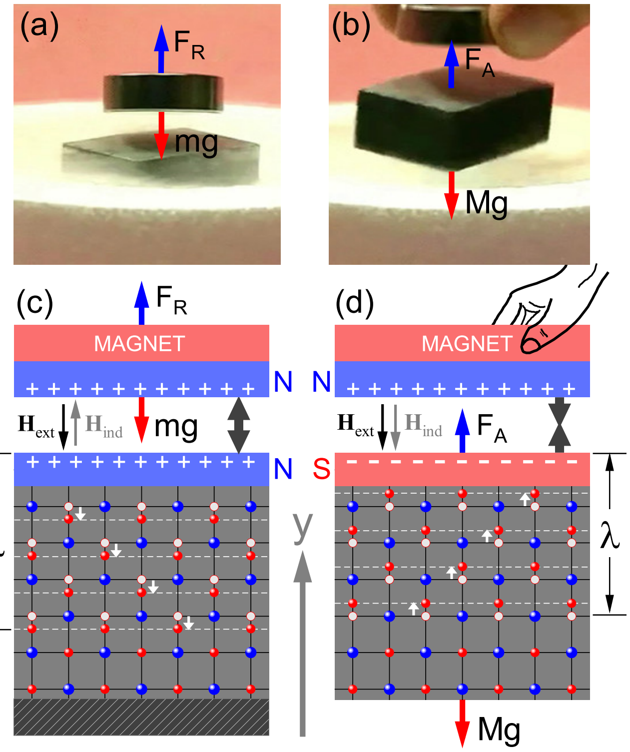

FIG. 4. The Meissner experiment and explanation: (a) and (b) observed repulsion and attraction interactions; (c) and (d) corresponding theoretical explanations.

that results in perfect symmetry breaking ($\theta_j = 0$, $y_j = 0$, $j = 1, 2...N$). The order parameter strictly aligns along the opposite direction of the electric field, and all electrons condense coherently into a single quantum state with zero resistance.

Apart from the four states mentioned above, the magnetic state is another essential natural phenomenon related to the metallic and superconducting states. Figs. 3(e) and (f) display unsaturated and saturated magnetic states, respectively, with microstructures consistent with those of metallic and superconducting states displayed in Figs. 3(c) and (d) correspondingly. In fact, the Messner effect shows that superconductors are magnetizable low-temperature magnets. Moreover, the figure shows that the material's electromagnetic properties are hidden (close state) when electrons are in the symmetrical Mott insulation state and released (open state) when symmetry is broken. The material's classification as a metal, magnet, or superconductor is determined entirely by the orientation order of the electron-proton (ion) electric dipole within it.

Besides zero resistivity, superconductors also exhibit impeccable diamagnetism, known as the Meissner effect. When cooled below their transition temperature in a weak magnetic field, superconductors conventionally expel the magnetic field from their interior. However, this explanation is inconsistent with experimental observations. Figs. 4(a) and (b) demonstrate repulsion and attraction between the

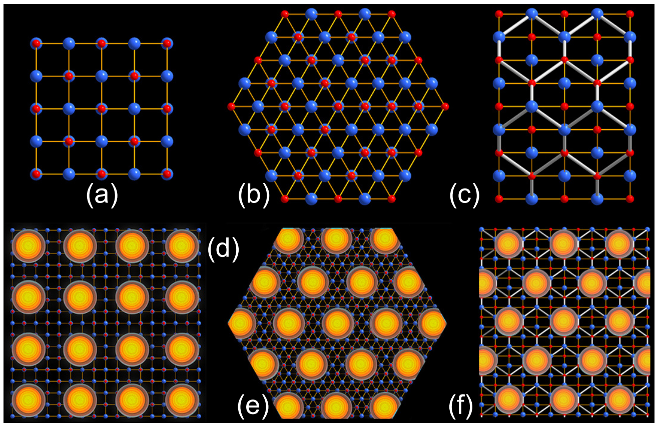

FIG. 5. Symmetry of 3D mott insulator (parent phase) and its corresponding vortex states (daughter phase). (a) [001] direction; (b) [111] direction; (c) [110] direction, respectively. The Abrikosov vortex lattices for these orientations are a square vortex, a triangular vortex, and a distorted hexagonal vortex, displayed in (d), (e), and (f), respectively.

superconductor and magnet, with the repulsion or attraction rapidly switching. Assuming the masses of the magnet and superconductor are m and M, respectively, the repulsive and attractive forces satisfy the force balance: $F_R = mg$ and $F_A = Mg$, where g is the acceleration of gravity.

In our theory, as shown in Fig. 4(c), a magnet $\mathbf{H}_{\text{ext}}$ above a superconductor causes the magnet to fall due to the gravitational field, increasing the strength of the magnetic field within the superconductor. This generates an induced magnetic field $\mathbf{H}_{\text{ind}}$ in the opposite direction and a repulsive interaction between the magnet and the superconductor due to the same sign of charges on adjacent surfaces. Fig. 4(d) shows that lifting the magnet away causes a decrease in magnetic field strength within the superconductor, generating an induced magnetic field $\mathbf{H}_{\text{ind}}$ in the same direction as, leading to mutual attraction between the magnet and superconductor due to the net charge on their nearest neighboring surfaces being of different signs. In the figure, λ is the London penetration depth, which automatically adjusts according to external factors such as the mass of magnets and superconductors to achieve force balance.

Abrikosov proposed the concept of the vortex lattice in type-II superconductors in his pioneering work [19]. However, the mechanism behind it remains at the macroscopic level. The fundamental question of how the magnetic field leads to the formation of vortex lattices is still challenging. Despite the wide range of classes and structures of superconductors, their vortex lattice structures exhibit similar symmetries. The symmetry of the vortex is closely linked to the orientation of the applied magnetic field. When the field is applied along the [110] of the fourfold, [111] the threefold, or [110] the twofold symmetric axis of the superconductor, square, triangular, or distorted hexagonal vortex lattices can be observed, respectively. The vortex structure can be considered a daughter phase, and their symmetry must have inherited the symmetry of the parent phase. So, what is the parent phase?

Fig. 5(a)-(c) display a $2 \times 2 \times 2$ super-cells of 3D Mott insulating electron-proton (ion) $NaCl$-type parent lattice along the fourfold, threefold, and twofold directions, respectively. As shown in Figs. 5(d)-(f), when an appropriate external magnetic field is applied, the electrons in the vortex cores absorb magnetic energy and are excited to a normal state, forming vortex structures that maintain the symmetry of the parent crystal. Once the upper critical field is reached, all valence electrons leave the ground state, and the superconductor returns to normal.

In conclusion, the superconducting theory of electron-proton pairing is established based on the Mott insulator, Maxwell displacement current, Dirac magnetic monopole, and Ginzburg-Landau symmetry-breaking theory. The new theory reveals the essence of magnetism, spin, magnetic monopole, and the order parameter of phase transition, unifies electric and magnetic fields, achieves symmetry of Maxwell's equations, and provides explanations for all superconducting phenomena and condensed physical phase transitions.

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