Unified Theory of Low and High-Temperature Superconductivity

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Abstract

Superconductors hold immense potential for various applications and could profoundly impact humanity. Despite extensive research, a room-temperature superconductor of practical value has yet to be achieved. The BCS theory cannot account for high-temperature superconductors. This issue may arise from the traditional model inaccurately attributing resistance to particle collisions of electron flow in conductors. This research proposes an alternative theory. According to the shear resistance, the state of matter can be a solid or a fluid. Likewise, the electrical resistance state of the same substance can be an insulator, a conductor, or a superconductor at different pressures and temperatures. These states are primarily determined by electron tunnels, which develop through molecular interactions. Within electron tunnels, electrons can move across molecules at the same potential level, resulting in currents. In conductors, electrons are confined to their molecules below the energy level of electron tunnels; energy is needed to elevate them into these tunnels to produce currents, causing electrical resistance. The resistance of a conductor can be decreased by compressing molecular spacing, as it minimizes the gap between valence orbitals and electron tunnels. With additional pressures, the gap can be further reduced to zero in superconductors, resulting in the intersection between valence orbitals and electron tunnels. Therefore, electrons can enter the tunnels without lifting energy, leading to zero resistance. This explains the inverse relationship between resistivity and pressure and why many high-temperature superconductors are achieved under high pressures. Molecular spacing decreases at low temperatures, as electrons move to lower orbitals. It reduces the pressure between molecules, mimicking the compressing effect. This elucidates the correlation between resistivity and temperature and why conventional superconductors are observed at low temperatures. In insulators, the electron tunnels are disconnected due to large molecular spacing. This spacing can be reduced with high pressures, thereby joining these tunnels. This is why some ceramics become superconductors under high pressures. This theory unifies insulators, conductors, and superconductors as dynamic resistance states of matter at different pressures and temperatures. The distinction between these states lies in the extent and connectivity of electron tunnels and the gaps between the tunnels and valence orbitals. A crucial insight from this theory for synthesizing room-temperature superconductors is the need to compress molecular distances. The significant barrier is the repulsion between molecules. Overcoming this repulsion with external pressures, as currently done to achieve most high-temperature superconductors, is impractical for most applications. An alternative approach may involve engineering molecular structures to leverage molecular attractions between certain molecules to overcome the repulsion.

Introduction

Since its discovery in 1911, superconductivity has been a popular research field due to its extraordinary properties and promising applications.[1-2] For instance, energy shortages are a key factor limiting economic growth, as seen in the training

of AI models. Ultimately, energy constraints the development of civilization across the universe. Fusion reactions offer a promising solution for a clean energy supply. One of the primary tasks in designing the tokamak fusion reactor is to use magnetic fields to confine the charged particles within the reactor. Generating these magnetic fields with normal conductor coils consumes so much energy. Superconductors are crucial for designing a tokamak fusion reactor capable of achieving breakeven energy production.

Cooper pairs of electrons, bound together by electron-phonon interactions, were proposed as the mechanism behind superconductivity in BCS (Bardeen-Cooper-Schrieffer) theory.[3] However, there are two key challenges to this theory. The first challenge concerns the assumption that a free electron attracts nearby nuclei, creating a high-density region of positive charge and thereby facilitating the electron-phonon interaction that binds Cooper pairs. In reality, each nucleus is surrounded by electron clouds that repel nearby electrons at short distances. As a result, instead of attracting surrounding nuclei, a free electron would tend to push them away, creating a low-density region of positive charge. This contradicts the basic premise of the electron-phonon interaction, raising questions about the physical foundation of the Cooper pair formation.

The second challenge to BCS theory arises from the observation of superconductivity at high temperatures. Electron-phonon interactions are generally believed to be significant only at low temperatures, as the vibrations of electrons and the crystal lattice weaken these interactions at higher temperatures, leading to the breakdown of superconductivity. However, since 1986, numerous superconductors have been discovered that exhibit superconductivity at temperatures well above the theoretical maximum predicted by BCS theory.[4-8] Furthermore, most high-temperature superconductors require high pressures to function, yet BCS theory fails to explain the positive effect of pressure on superconductivity.

BCS theory also fails to explain many observed phenomena in superconductors, which will be discussed later in this article.[9] The issue may lie in the incorrect assumptions underlying the Drude model of electrical resistance, which is implicitly incorporated into the BCS framework. According to the Drude model, conductors contain a sea of free electrons that flow through the material to generate electric current. Electrical resistance arises from collisions between these free electrons and the atomic lattice, with each collision scattering the electrons and dissipating energy. In BCS theory, it is assumed that the formation of Cooper pairs minimizes these electron-lattice collisions, thereby reducing resistance and enabling superconductivity.

However, the assumptions underlying the Drude model are not fully proven. According to the conventional model of conductors, free electrons form a "sea of electrons" that acts as a kind of glue between the atomic nuclei, creating metallic bonds. The stability of a conductor's structure relies on the strength of these metallic bonds. But what happens if this sea of electrons is removed from the conductor? The atomic nuclei, which form the lattice, would repel each other, causing the structure of the conductor to collapse. The concept of a free-moving electron sea implies that the bonding "glue" holding the metallic lattice together is not localized. This raises the question: how can the conductor's structure remain stable with such an inherently unstable form of bonding? In reality, conductors are highly stable and can withstand significant shear and tension forces. This calls into question the validity of both the electron sea model and the traditional understanding of metallic bonds.

In addition, the traditional model of electrical resistance faces similar challenges at high pressures. The Drude model posits that electrical resistance arises from collisions between flowing electrons and the lattice in conductors.[10] If this model were

accurate, high-density materials should exhibit higher resistance. As pressure increases, the atoms in a conductor are packed more tightly, leading to more frequent collisions between electrons and the lattice, and thus, higher resistivity. However, experimental observations reveal the opposite: resistivity actually decreases with increasing pressure.[11-13] This trend holds all materials, from insulators to conductors to superconductors. Under high pressure, resistance continues to drop and can eventually reach zero, as seen in many high-temperature superconductors. Notably, many of superconductors are not metals, such as ceramics, which become superconducting only under high pressure. These findings challenge the assumptions of the Drude model, suggesting that a more nuanced understanding is needed to explain electrical resistance and superconductivity.

The failures of these theories on resistivity and superconductivity at high pressures may not be coincidental but a consequence of incorrect assumptions in the collision model for electrical resistance and misconceptions of electron sea. These may have misled researchers and hindered theoretical and practical progress in the field, particularly in searching for room-temperature superconductors.

Rather than treating resistivity and superconductivity as distinct states of matter, we believe they should share the same physical mechanism. An alternative theory is proposed in this study with the introduction of a concept for the electron tunnel, which develops between molecules in materials at a close distance. The resistivity of substances is determined by the spacing between molecules, a dynamic variable influenced by pressure and temperature. Therefore, electrical resistivity correlates with pressure and temperature, which determine the electrical state of matter.

In the following sections, we will introduce key concepts that form the foundation of our theory, using simplified models. By examining the crystal structure of simple molecules, we can develop mathematical models that predict the existence of electron tunnels and explain the properties and behaviors of both conductors and superconductors. These models suggest that superconductivity is not an exceptional state, but rather a common phase of matter, particularly at high pressures. Furthermore, the transition between different electrical phases—superconducting, conducting, and insulating—can be understood as a result of changes in the spacing between molecules, which are influenced by pressure and temperature. These models provide valuable insights into electrical resistivity and offer guidance for overcoming the challenges in the quest for room-temperature superconductors.

Note that the models used in this study are simplified to illustrate the concepts in the new theory. The actual structure of electron tunnels can be much more complex for large molecules to model mathematically. Nevertheless, the concepts should be extensible and applicable to synthesizing room-temperature superconductors.

Introduction to Electron Tunnel

Electron tunnels refer to the network of electron paths between molecules in a conductor, allowing electrons to flow at the same potential/energy level across molecules and resulting in currents. An electron with an energy level below that of the electron tunnels remains confined within its orbital inside the host atom or molecule and, therefore, cannot produce current. To create currents in a conductor, electrons must reach a sufficient energy level to move through the electron tunnels. Thus, the space in a conductor is divided into two regions: an interconnected network of electron tunnels between molecules and isolated cells around individual atoms or molecules. In insulators, these tunnels are disconnected.

A superconductor is a unique type of conductor where valence orbitals extend into and overlap with electron tunnels. Consequently, the valence electrons can naturally enter the electron tunnels without needing additional energy to elevate them. To illustrate the concept of electron tunnels, let's consider a simple model. Place a proton next to a hydrogen atom as shown in Figure 0. At the quantum level, the electron should be found around the hydrogen atom with a high probability at a relatively large distance from the proton. This probability diminishes as their distance reduces, resulting in electron distribution probability current flowing toward the proton. At a certain distance, the electron distribution density will become balanced between the two protons, meaning the electron effectively flows between them.
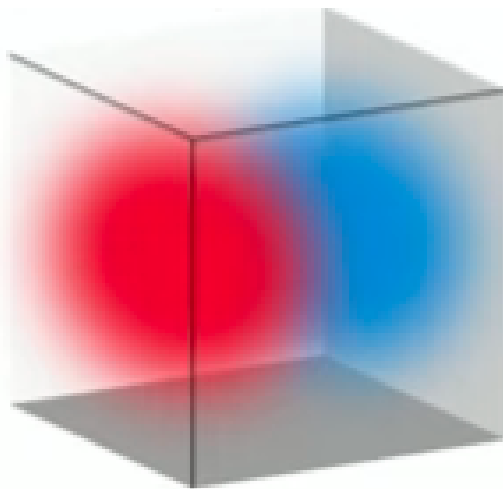

Figure 0, A quantum model of a hydrogen atom next to a proton.

If multiple protons are packed closely together at a sufficiently small distance, an electron can move freely between them, creating a current and resulting in superconducting hydrogen. In this sense, a hydrogen molecule functions as a superconductor for the shared electron between the two protons. The electron path between the protons forms what we refer to as an electron tunnel. Similarly, covalent bonds between atoms can also create electron tunnels, effectively acting as local superconductors.

In the model above, the electron in hydrogen is attracted to the proton when it is sufficiently close. At what distance does this attraction occur? This distance determines the formation of superconducting tunnels. While the answer can, in principle, be found by solving the Schrödinger equation with this model, this approach quickly becomes too complex when extended to more comprehensive models. Instead, a simpler approach using well-established classical physics discussed next, will effectively illustrate the concept of electron tunnels.

As shown in Figure 1, R_b represents the distance from the nucleus center to the border (i.e., the middle for simplicity now) between the proton and hydrogen. R_v is the radius of the valence orbital, which may change depending on temperature.[14] Therefore, the problem becomes to find the R_b so that the electron will be pulled over to the proton.

The electron cloud and orbital shape should undergo certain deformation as atoms come close, inducing different fields and bonds between them. This phenomenon will be explored in subsequent discussions, particularly in the context of compression bond formation. For the sake of simplicity, we are presently ignoring this effect. An attraction coefficient will be introduced to address the uneven attraction fields between molecules. The electron tunnels will be realized later with

bonds for the interaction between molecules. Also note that valence electrons in this discussion refer to the outmost electrons in an atom, not necessarily in the ground state.
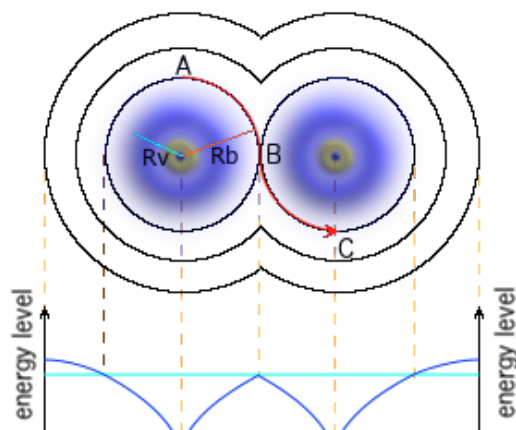

Figure 1, Concept of electron tunnel illustrated using a simple model involving a hydrogen atom adjacent to a proton. In this model, the valence electron is attracted by both its host nucleus and the neighboring proton. The electron tunnel between the hydrogen atom and the proton enables the electron to move from one to the other. In the diagram, the blue short stroke represents the radius of the valence orbital, denoted by R_v, and the red stroke indicates the radius to the border between the hydrogen atom and the proton, denoted by R_b. The contours show the orbitals at different energy levels intersecting with a plane passing through the centers of the protons. The blue curves in the lower part of the figure represent the potential level of the protons as a function of the distance from the center of each proton. An electron in the electron tunnel may drift from one proton to the other along a path at the same energy level, such as the path A-B-C.

To find the answer to the question above, we need to compute the energy required to raise an electron along the center line between the nuclei from its orbital r to the border R_b. This involves calculating the total energy difference between R_b and r. The electron is attracted to both its host nucleus and the adjacent proton through Coulombic force:

(1) $F = \dfrac{Kq_1 q_2}{d^2}$

where K is Coulomb's constant, and negative F represents the attraction between charges q_1 and q_2 at a distance d. The Coulomb force F_e to an electron along the center line between the proton and hydrogen nucleus will be

(2) $F_e = KQe\left[\dfrac{1}{r^2} - \dfrac{1}{(2R_b - r)^2}\right]$

where Q represents the charge of a proton, e is the charge of an electron, and r indicates the orbital radius of a valence electron. The potential difference E_u for the electron is the work needed to move the electron against the force F_e from orbital r to R_b, which can be calculated by integrating the force F_e over the distance from r to R_b:

(3) $\quad E_u = -\int_r^{R_b} F_e\, dx$

$$= -\int_r^{R_b} KQe\left[\frac{1}{x^2} - \frac{1}{(2R_b-x)^2}\right]dx$$

$$= -KQe\left[\frac{1}{r} + \frac{1}{2R_b-r} - \frac{2}{R_b}\right]$$

The difference in kinetic energy must also be taken into consideration. When an electron is circulating at a distance d from its nucleus, its centripetal force is

(4) $\quad F_c = ma$

$$= m\frac{v^2}{d}$$

where m represents the mass of the electron, a is the acceleration, v indicates the velocity, and F_c is balanced by the force given in Equation (2), i.e., $F_c = -F_e$. The negative force in Equation (2) indicates an attraction. The kinetic energy at the border R_b becomes

(5) $\quad E_{R_b} = \frac{1}{2}mv^2$

$$= -\frac{KQe}{2}\left[\frac{R_b}{R_b^2} - \frac{R_b}{(2R_b-R_b)^2}\right]$$

$$= 0$$

The kinetic energy at orbital r will be

(6) $\quad E_r = \frac{1}{2}mv^2$

$$= -\frac{KQe}{2}\left[\frac{1}{r} - \frac{r}{(2R_b-r)^2}\right]$$

The kinetic energy difference between R_b and r is

(7) $\quad E_k = E_{R_b} - E_r$

$$= -\frac{KQe}{2}\left[\frac{r}{(2R_b-r)^2} - \frac{1}{r}\right]$$

The total energy to lift the electron from r to R_b will be

(8) $\quad E = E_k + E_u$

$$= -\frac{KQe}{2}\left[\frac{1}{r} + \frac{2}{2R_b - r} + \frac{r}{(2R_b - r)^2} - \frac{4}{R_b}\right]$$

Equation (8) can be visualized as a 3D surface, representing the lifting energy on the r-R_b plane. Alternatively, given a specific value of r, it can also be illustrated by a 2D curve that shows the lifting energy as a function of R_b. To find the answer to the problem raised earlier, we simply need to solve Equation (8) at $E = 0$, and the solution is

(9) $\quad R_b = \frac{3+\sqrt{5}}{2}r$

$\quad\quad \approx 2.618r$

This means that when the proton is placed at a distance of 5.236r (i.e., 2x2.618r) from the center of the hydrogen atom, the valence electron can be attracted toward the proton. Consequently, the drift can occur when the electron is at an orbital radius r, well below the border R_b (=2.618r). The orbital radius range between r and 2.618r is the drift zone. In other words, an electron can drift between two protons along the central region, which has a width of 3.236r, representing part of the electron tunnel between the protons.

Consider a crystal with such molecules placed at this distance next to each other. The central regions between these molecules would connect into tunnels, allowing electrons to move freely at the same energy level, thereby forming a continuous electron tunnel.
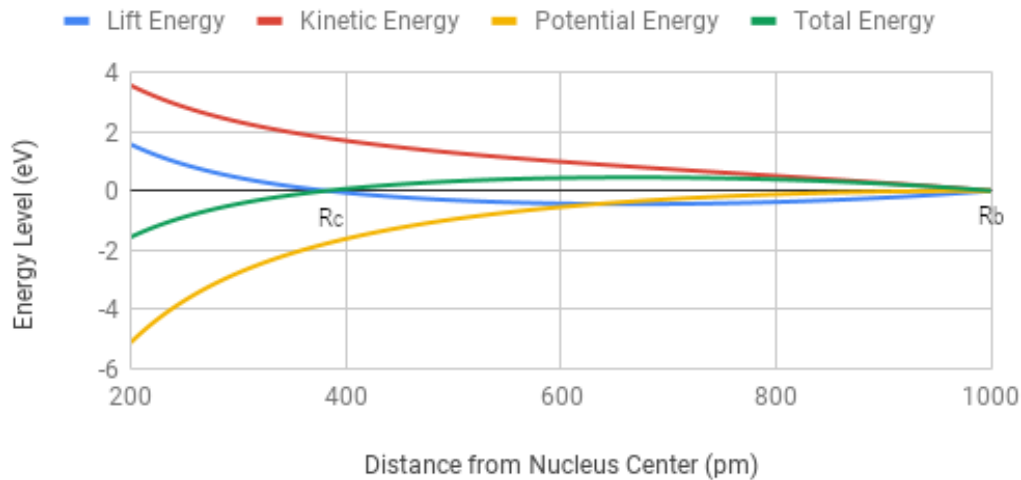

Figure 2, Required energy to raise an electron in a hydrogen atom to the border between the atom and a proton placed 2000 pm apart. The blue curve represents the energy needed to elevate an electron to the border between the nuclei as a function of the electron's orbital radius. The x-axis starts at the hydrogen center and extends to the proton on the right. R_b represents the distance to the border. In this example, its value is 1000 *pm* for calculating the lifting energy using Equation (8). The lifting energy decreases from a positive value as the electron orbital radius increases towards the border. R_c represents the electron radius where the required lifting energy becomes zero and turns negative beyond that point. A negative lifting energy value implies that the electron is no longer confined to its

nucleus. The locations with negative lifting energy represent the region in the electron tunnel between the protons. The figure only plots the portion on the hydrogen side, with the complete picture being symmetric and mirrored along the border. For reference, the kinetic energy of the electron (in red) based on Equation (7), the potential energy (in yellow) derived from Equation (3), and the total energy (in green) are also plotted. The total energy is the sum of the kinetic and potential energies, representing the inverse of the lifting energy (in blue).

Alternatively, we can view the problem from a different perspective by looking at Equation (8) as a curve that shows the energy required to raise an electron at r with a given R_b, as illustrated by the blue curve in Figure 2. The curve indicates the energy needed to elevate an electron to the border decreases as the electron's orbital radius increases. The lifting energy reaches zero at a particular radius R_c, which can be inverted from Equation (9):

$$(10) \quad R_c = \frac{3-\sqrt{5}}{2} R_b$$

The interpretation of Equation (10) is that when an electron's orbital radius is greater than R_c, it can drift toward the proton without additional energy. This means that when a valence electron is at this radius or higher, it tends to move towards the proton, signifying that the electron is liberated from its host and potentially leading to the generation of currents. Consequently, R_c is referred to as the conducting radius, which represents the condition for initiating a current across molecules in a conductor, i.e.,

$$(11) \quad R_v \geq R_c$$

where R_v refers to the orbital radius of valence electrons. In this view, the electron tunnel can be defined as the region above the conducting radius between molecules. Since Figure 2 only plots the curves on the hydrogen side, the space between R_c and R_b is just half the width of the electron tunnel. Whenever valence electrons are in this region, indicating they are within the electron tunnel, they can drift between molecules, creating electrical currents.

The significance of R_c lies in its role as the dividing point for an electron's liberating orbital. When an electron's orbital radius is lower than R_c, it remains in an orbital confined to its host atom and molecule. Electrons may experience perturbations in their orbitals. As an electron is perturbed to a higher level, its potential energy increases at the expense of kinetic energy. However, the kinetic energy reduction cannot compensate for the rise in potential energy. This energy deficit, represented by the negative value in Figure 2's green curve, indicates that the kinetic energy decreases more than necessary to maintain the electron's speed at a higher level. As a result, the slower-moving electron tends to return to its equilibrium orbit corresponding to its energy level. Likewise, when an electron wanders into a lower energy level, the reduced potential energy is converted to kinetic energy. The excess kinetic energy also causes it to revert to its equilibrium orbit. Thus, without additional energy, an electron below R_c may experience perturbation but is still confined in its orbital inside its host.

On the other hand, an electron with an energy level at an orbital radius greater than R_c is no longer bound to its host atom. When it is perturbed to a higher level, the excess kinetic energy, represented by the positive value of the green curve in Figure 2, propels it to an even higher level beyond the control of its host nucleus. The electron is effectively liberated and drifts towards the proton. Upon gaining the electron, the proton transforms into a hydrogen atom, while the nucleus of the original host hydrogen becomes a single proton. As a result, the hydrogen-proton setting flips to a proton-hydrogen setting.

Likewise, the electron can also drift back to the initial hydrogen nucleus. Therefore, the electron becomes a shared electron between the two protons, similar to a covalent bond. Indeed, a covalent bond forms through a similar interaction; however, there is a notable difference. In an H_2 molecule's covalent bond, the two electrons are bound so tightly to their nuclei that they cannot escape the molecule to generate currents. Thus, a solid of H_2 is not a conductor.

In contrast to the tightly bound, the electron in the hydrogen-proton model may not be restricted if other protons are nearby such as in metallic hydrogen. Indeed, to generate currents, a disconnected electron tunnel between just two molecules is insufficient; a well-connected electron tunnel between surrounding molecules is required. Consider a metallic hydrogen crystal with one or more protons. The electron tunnels between the atoms can be fully connected, creating a network for electron flow. An electron with an energy level within the electron tunnels can drift along the isoenergy level across different atoms/molecules, rather than being confined to any individual H_2 molecules. The movement of electrons in the electron tunnels produces currents. The significance of the electron tunnels lies in their function as a shared network of electron paths at the same energy level, facilitating a smooth flow of electrons between molecules.

In an isolated hydrogen atom, without a nearby proton, the total electron energy at any orbital level is negative and approaches zero at infinity. The positive energy depicted in Figure 2 is due to the influence of the nearby proton, which implies that the electron tunnel results from the proton's influence.

The interaction discussed so far involves a hydrogen atom and an adjacent proton. Similarly, a molecule with an electron-hole can produce an effect similar to a proton, forming an electron tunnel with a neighboring molecule. Furthermore, this model will be extended and generalized later to accommodate more realistic interactions through typical intermolecular bonds.

Intermolecular Bond Due to Compression

Unlike in an isolated atom, the electrons of atoms and molecules in a conductor are influenced by the electric fields of adjacent molecules, causing the electrons to adjust their clouds and redistribute. Uneven electron distribution induces local electric fields, such as London dispersions,[15] resulting in various types of bonds between molecules. Molecules are held together in solids by these bonds. Viscosity in fluids is due to intermolecular bonds. Attractions between molecules are universal and can facilitate the development of electron tunnels, which is why the previously discussed model can be extended and generalized.

As an example of intermolecular bonds, let's explore a novel type of bond induced between molecules under pressure, known as the compression bond, which was predicted in a study of superfluidity.[16] The London dispersion creates attractions between normal helium molecules, resulting in viscous helium fluids. As helium electrons retreat to lower orbitals at low temperatures, the London dispersion is weakened and eventually destructed, as shown in Figure 3A. In the absence of intermolecular attraction, there is no viscosity, and helium molecules become superfluid. Hence, a superfluid is not a fluid but a collection of individual molecules. Without any attraction between molecules, a solid cannot be obtained by cooling the superfluid further. Pressure must be applied to obtain solid helium.[17]

Helium molecules become tightly compressed under pressure. Under the electrical repulsion from adjacent molecules, the electron cloud of each molecule contracts along the axis through the two protons, as shown in Figure 3B. This uneven

density of electron distribution in different directions generates local electrical fields with positive along the proton axis and negative at the periphery of the plane perpendicular to the axis.

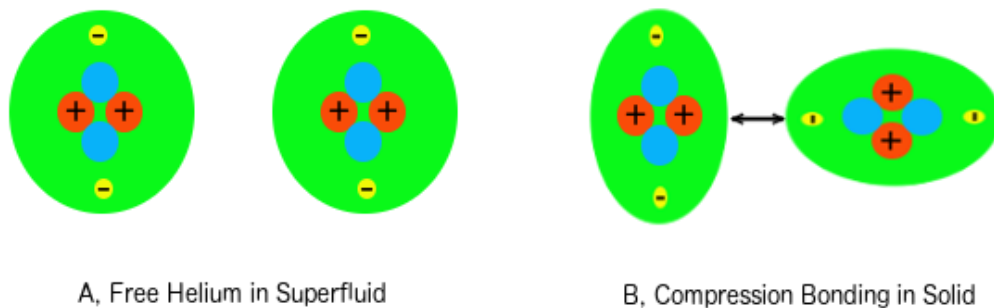A, Free Helium in Superfluid   B, Compression Bonding in Solid

Figure 3. Compression bonds developed between helium molecules at high pressures. (A) Under normal pressures on Earth, superfluids can be obtained from liquid helium by lowering the temperature to the point where the London dispersion disappears. However, unlike most substances, solid helium cannot be produced by further reducing the temperature because there is no attraction to hold the molecules together. Pressure must be applied to obtain solid helium. (B) Under high pressures, the electron cloud of each molecule contracts along the axis through the two protons. This uneven distribution in electron density in different directions creates local electric fields, resulting in an attraction between molecules, named the compression bond. Solid helium is molecules held together by these bonds.

Attractive forces arise between the positive and negative fields, driving the molecules to reorient themselves to minimize their potential energy. Eventually, the molecules achieve a minimum energy arrangement, as depicted in Figure 3B, resulting in the compression bonds between them. Figure 3B illustrates the smallest arrangement of two molecules held together by this bond. Compression bonds are responsible for holding molecules together in solid helium.[16]

In the normal state of hydrogen, the covalent bond between two hydrogen atoms in an H_2 molecule may be considered an isolated electron tunnel between the atoms, which allows the electrons to travel between them. However, the repulsion between H_2 molecules separates the molecules at a considerable distance, preventing the local electron tunnels in H_2 molecules from connecting into a network. Without a connected network, electrons cannot move between different H_2 molecules. As a result, a normal hydrogen liquid is an insulator. However, under high pressure, hydrogen becomes metallic.[18-19] It is believed that the normal covalent bonds between hydrogen atoms yield compression bonds at high pressures,[16] resulting in interconnected electron tunnels, which transition normal H_2 molecules into metallic hydrogen.

Compression bonds may be prevalent in single-atom molecule substances, as nearly everything on Earth is subject to certain pressures. The attractive force of compression bonds facilitates the development of electron tunnels between molecules, similar to the mechanism discussed in the previous section. The formation of electron tunnels in most conductors and superconductors may be related to the development of compression bonds.

Current, Resistance, and Superconductivity

To understand the phenomena of current, resistance, and superconductivity, we must first correct some misconceptions about these concepts in traditional models, particularly the collision model for electrical resistance. Many theories and models implicitly assume that currents are electrons flowing in the free space between molecules in conductors. However, this assumption is flawed because the space between molecules in conductors is never truly free for electrons.

From a large distance, an atom appears electrically neutral. When atoms are close, electrical fields are induced between them, resulting in various forces that hold them together. Without attractive forces between molecules, there would be no solids or fluids, only individual molecules, such as in superfluids. The fact that most substances exist in solids or viscous fluids indicates that attraction between molecules is prevalent. Therefore, the space between molecules is never a vacuum but is typically filled with electrical fields.

With a negative charge, an electron is influenced by these fields and typically cannot move freely, either within an atom or molecule or between molecules in a conductor. Within an atom or molecule, an electron is confined to and moves within its orbital, corresponding to its energy level. Although perturbations can occur, an electron cannot change its orbital without exchanging energy with its surroundings, such as by emitting or absorbing photons.

An atomic electron is confined by the electrical field created by its nucleus, defining an orbital. An electron tunnel can be perceived as a special orbital or an electron path shared between multiple molecules. For an electron to move through an electron tunnel, the electron must possess the corresponding energy. Below this energy level, the electron is confined to the host atom of an individual molecule. Above this energy level, the electron is effectively liberated from the control of the molecule and capable of flowing through the electron tunnel across different molecules, resulting in a current.

An electron may drift along electron tunnels from one atom to the next in a different molecule, creating a current with a negative charge in a conductor, called electrodrift. During an electrodrift, the energy level of the electron does not change. Before an electron can drift in electron tunnels, it must absorb additional energy to excite into an electron tunnel. An electron hole is left behind after the electron drifts to the next molecule. The hole may be filled later by another electron. A series of drifts of an electron-hole results in a current with a positive charge, similar to the flow of a cation. Hence, currents can be the flows of both negative and positive charges.

There is normally no current in a conductor although electron tunnels may exist. This tunnel, or the space between molecules, is not empty but separated by potential barriers, as illustrated in Figure 4A. For an electron to move from one molecule to the next, it has to overcome these energy barriers. Energy must be added to an electron to elevate it to electron tunnels to create a current across molecules. An electron may be raised to the electron tunnels in an electrical field, such as an applied voltage, or a magnetic field, as in an electrical generator.

The lifting energy is the work against the Coulombic force between the electron and its host nucleus. After gaining extra energy, an electron can excite and flow in the electron tunnel across molecules, forming a current. Once in a while, the electron may fall into an electron hole. The previously stored energy will eventually dissipate through emitting electromagnetic waves. Therefore, the cause of electrical resistance is the loss of the energy gained from the work done against the Coulombic force, not the collisions between particles as conceived in the traditional model.
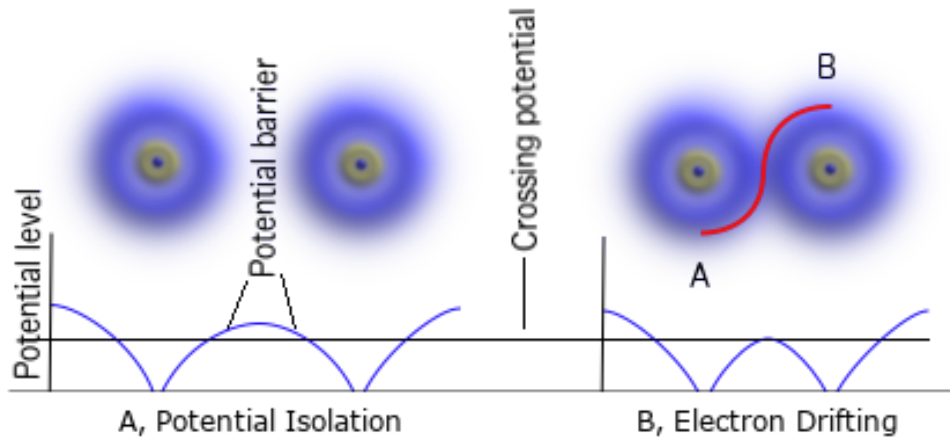
Figure 4, Difference between normal conductors and superconductors. As shown in the figure, each atomic nucleus generates an electrical field that attracts the surrounding electrons. The blue curves in the lower part of the figure represent energy/potential level. The horizontal direction indicates the distance from the respective nucleus center, and the vertical direction is the potential scale. (A) At a considerable distance between two atoms/molecules, their electrons are separated by an energy barrier. To enable electrodrift, energy is needed to elevate electrons to the electron tunnel along the border, which is the cause of electrical resistance in conductors. (B) In superconductors, there is no such barrier as the distance between molecules is smaller such that valence orbitals intersect electron tunnels. This distance can be reduced by increasing pressure or decreasing temperature, pushing the electron tunnel lower to overlap the valence orbitals and allowing electrons to drift from one molecule to the next without lifting energy, as illustrated by the red path A-B.

Unlike in normal conductors where electron tunnels are located at an energy level above valence orbitals, in superconductors, valence orbitals intersect electron tunnels. This overlap allows valence electrons to enter electron tunnels without a need for lifting energy to drift between molecules, as shown in Figure 4B. Thus, electrodrifts occur naturally in superconductors without lifting energy, resulting in zero resistance, therefore achieving superconductivity. Electron tunnels can be dynamically pushed lower to overlap valence orbitals by increasing pressure or decreasing temperature, which will be discussed in more detail later.

At a temperature above 0 K, a conductor absorbs energy from and emits energy to the surroundings. At equilibrium, the net exchange of energy is zero. The valence electrons in a conductor should be at an average energy level above the ground orbitals. From the perspective of an electron, the total energy E_t needed to elevate from the ground orbital to the electron tunnel can be broken down into two constituents: E_v the energy required to rise from the ground orbital to the valence orbital, and E_c the energy needed to lift from the valence orbital to the electron tunnel:

(12) $\quad E_t = E_v + E_c$

At the equilibrium, E_v is maintained or supplied by the environment. E_c is the additional energy needed to raise the electron to the electron tunnel, which represents the work required to create currents in a conductor and is the cause of electrical resistance. When valence orbitals overlap electron tunnels, as in superconductors, the additional lifting energy is unnecessary for electrodrift, i.e., $E_c = 0$. Thus, Equation (12) can be simplified to

(13) $E_t = E_v$

This equation indicates that the total lifting energy for electrons in superconductors is constantly supplied from the environment. This predicts the positive relationship between critical current density and critical temperature of superconductors, which will be discussed in more detail later in the critical current density section.

From the environment's perspective, the energy loss is compensated by the energy radiated from the superconductors at the equilibrium. The entire system is energy-conservative given there is no energy taken out of the system. Thus, although currents and magnetic fields exist in superconductors, their energies cannot be harvested for free.

Theoretically, when a superconductor is at the absolute zero temperature, there is no energy exchange between the superconductor and the environment. The valence orbitals are at the ground level. Equations (12) and (13) still hold because

(14) $E_t = E_v = E_c = 0$

Extended Model for Electron Tunnel

The electron tunnel concept introduced so far is based on a simplified model involving a hydrogen atom adjacent to a proton. Electron tunnels can be developed in various bonds resulting from molecule interactions. At small distances, the outer shells of electron clouds in atoms/molecules are typically distorted, resulting in electrical field variations and inducing intermolecular bonds. These bonds are crucial to the development of electron tunnels. It is important to note that molecular bonds, such as covalent bonds, enable electrons to move between atoms within individual molecules but do not allow electron movement across different molecules necessary for current generation. The bonds discussed here are intermolecular bonds, such as compression bonds, that facilitate currents across molecules through an interconnected network of electron tunnels in conductors.

To investigate the influence of bond strength on the development of electron tunnels and to determine the extent of these tunnels in a conductor, we introduce a concept known as the attraction coefficient, denoted by the symbol c. This coefficient quantifies the strength of the bond attraction exerted on an electron by an adjacent molecule. Assume that an electron is attracted to its host nucleus by an equivalent charge Q. The attraction to the electron by an adjacent molecule with a bond strength c is modeled as if it arises from a charge of cQ. The value of c typically does not exceed 1. Using this coefficient, the force exerted on the electron by both molecules can be modeled. As a result, the energy level of the electron and the potential fields between molecules can be determined along the center line between the molecules.

To estimate the energy required to lift an electron from orbital r to the border R_b, we need to include both forces exerted on a valence electron by two adjacent molecules in a conductor. By incorporating the coefficient c, we can refine Equation (2) in the previous model to

$$(15) \quad F_e = KQe\left[\frac{1}{r^2} - \frac{c}{(2R_b-r)^2}\right]$$

where $c \leq 1$ denotes the attraction coefficient between adjacent molecules. When $c = 1$, the model represents a normal molecule next to a molecule with an electron hole, similar to a hydrogen atom next to a proton, as described in Equation (2). When $c = 0$, it may simply represent a situation of a single molecule without adjacent molecules. When $c < 0$, it simulates molecular repulsion, which may occur between certain atoms or molecules in insulators. When $0 < c < 1$, it models various bond strengths between molecules. Indeed, it will become clear later that the value of c signifies the difference between insulators, conductors, and superconductors. When c is small enough, such as $c < \frac{1}{5}$, the model represents weak bond strengths, typically found in insulators. Otherwise, when $\frac{1}{4} < c < 1$, it simulates various bond strengths between molecules in conductors and superconductors.

Next, let's extend the model to include the forces from two molecules located along the center line on the farther sides of the two initial molecules in the crystal lattice. Equation (15) needs to be adjusted accordingly as:

$$(16) \quad F_e = KQe\left[\frac{1}{r^2} - \frac{c}{(2R_b-r)^2} + \frac{c}{(2R_b+r)^2} - \frac{1}{(4R_b-r)^2}\right]$$

Now, also consider the influences from two molecules further down the line, and so on. The accumulated forces exerted on the electron from all the molecules along the center line is the sum of the Coulomb force from each molecule:

$$(17) \quad F_e = KQe \sum_{i=0}^{N}\left[\frac{c^{i\%2}}{(2iR_b+r)^2} - \frac{c^{(i+1)\%2}}{(2(i+1)R_b-r)^2}\right]$$

where the symbol % represents the modulo operator or MOD, and N refers to the number of molecules along the line of the two molecules in consideration, which should be a sizable number depending on the dimensions of the conductor. In the crystal lattice of a conductor, molecules are surrounding this line. However, for a sizable conductor, it is reasonable to assume that the influences from surrounding molecules will cancel each other out. Therefore, we only need to consider the molecules along the line, and Equation (17) should be sufficient for the model. Additionally, the model can be further generalized for large molecules by interpreting Q as an equivalent positive charge that exerts the Coulombic force on the electron while accounting for the influence of other electrons.

Now, the potential energy difference E_u or the energy needed to move the electron along the line from orbital r to the border R_b between the two molecules can be computed by integrating over the force provided in Equation (17) from r to R_b:

$$(18) \quad E_u = - \int_{r}^{R_b} KQe \sum_{i=0}^{N}\left[\frac{c^{i\%2}}{(2iR_b+x)^2} - \frac{c^{(i+1)\%2}}{(2(i+1)R_b-x)^2}\right]dx$$

$$= - KQe \sum_{i=0}^{N}\left[\frac{-c^{i\%2}}{2iR_b+x} + \frac{-c^{(i+1)\%2}}{2(i+1)R_b-x}\right]_{r}^{R_b}$$

$$= -\frac{KQe}{2} \sum_{i=0}^{N} D_u(i)$$

where

(19) $$D_u(i) = \frac{2c^{i\%2}}{2iR_b+r} + \frac{2c^{(i+1)\%2}}{2(i+1)R_b-r} - \frac{2c^{i\%2}+2c^{(i+1)\%2}}{2iR_b+R_b}$$

The kinetic energy for the electron at the distance r from the nucleus along the line can also be calculated from Equation (17):

(20) $$E_r = -\frac{KQe}{2} \sum_{i=0}^{N} \left[\frac{rc^{i\%2}}{\left(2iR_b+r\right)^2} - \frac{rc^{(i+1)\%2}}{\left(2(i+1)R_b-r\right)^2} \right]$$

The kinetic energy difference between R_b and r is

(21) $$E_k = -\frac{KQe}{2} \sum_{i=0}^{N} D_k(i)$$

where

(22) $$D_k(i) = \frac{rc^{(i+1)\%2}}{\left(2(i+1)R_b-r\right)^2} - \frac{(c^{(i+1)\%2}-c^{i\%2})R_b}{\left(2iR_b+R_b\right)^2} - \frac{rc^{i\%2}}{\left(2iR_b+r\right)^2}$$

The total energy E_c to elevate the electron from orbital r to the border R_b between the two molecules is the sum of the potential energy and kinetic energy estimated in Equations (18) and (21), respectively:

(23) $$E_c = E_u + E_k$$
$$= -\frac{KQe}{2} \sum_{i=0}^{N} \left[D_u(i) + D_k(i) \right]$$

It is important to note that the summation term in the equation above captures two microscopic properties of a conductor: the bond strength between molecules and the distance from the valence orbital to the electron tunnels. These two properties determine many characteristics of conductors. For easy reference later, let's call this term the "resisting distance".

(24) $$D = \sum_{i=0}^{N} \left[D_u(i) + D_k(i) \right]$$

The resisting distance of a conductor determines the energy required to generate currents and therefore influences the electrical resistivity of the conductor. This term encapsulates the differences between insulators, conductors, and

superconductors. Additionally, the resisting distance governs the dynamic behavior of a conductor under varying pressures and temperatures. With the concepts and models established so far, we will now apply and validate them through observations. The next section will first explore the predictive power and role of resisting distance in explaining the observed properties of conductors and superconductors.

Electrical Resistivity Originating from Resisting Distance

The electrical resistance of a conductor is described in Ohm's law, which is an empirical relation obtained from experiments. What are the fundamental microscopic properties of a conductor that give rise to this law? In this section, we will explore the relationship between a conductor's resistivity and its macroscopic properties related to the resisting distance.

The energy estimated in Equation (23) represents the minimum energy required to elevate a valence electron to the electron tunnel for creating a current. Thus, the lifting electrical potential for the electron is

$$(25) \quad v = \frac{E_c}{e}$$

where e is the charge of an electron. Assume a total voltage V is applied to the ends of a conductor with a length L and a cross-section area A. This voltage raises and drives n electrons through the conductor in T seconds. Hence, V provides the total potential to create the current of the n electrons, which relates to the potential v for driving individual electrons. At the microscopic scale, the voltage V applied to the conductor by a power supply, such as a battery, is through the accumulation of electrical charges at the ends of the conductor, which provides the potential to lift electrons near the ends. The lifted electrons create a potential field further into the conductor, which in turn provides the potential field to drive electrons further into the conductor, and so on. Therefore, V should be proportional to the lifting potential v and the number of electrons (n) and they can be related by introducing a coefficient p:

$$(26) \quad V = pnv$$

By definition, the current I created by V is

$$(27) \quad I = \frac{en}{T}$$

Combining Equations (25), (26), and (27), we find the relation between electrical resistance R and lifting energy E_c based on Ohm's law:

$$(28) \quad R = \frac{V}{I} = \frac{pTE_c}{e^2}$$

By definition, the resistivity of a conductor is

(29) $\rho = R\frac{A}{L} = \frac{pATE_c}{Le^2}$

Replacing E_c provided in Equation (23), the electrical resistivity becomes

(30) $\rho = -\frac{pATKQ}{2Le}D$

Note, the speed of electrons drifting in a conductor is

(31) $s = \frac{L}{T}$

which is a property specific to a conductor. By introducing an equivalent coefficient u for the nucleus charge of molecules in the conductor, Q can be expressed as

(32) $Q = -ue$

And, Equation (30) can be simplified to

(33) $\rho = \frac{puAK}{2s}D$

For hydrogen, u = 1. As atom size increases, the valence elections experience less influence from the host nucleus and u < 1. By introducing a property Z, namely microscopic resistivity, which encapsulates the Coulomb's constant and microscopic properties p, u, and s specific to a conductor,

(34) $Z = \frac{puAK}{2s}$

the resistivity can be simplified as

(35) $\rho = ZD$

This equation indicates that the electrical resistivity of a conductor is determined by its microscopic resistivity (Z) and resisting distance (D). Z represents the constant properties of a conductor at the microscopic scale, while D encapsulates the dynamic properties: R_v, R_b, and c. D depends on the spacing between molecules and changes dynamically with pressure and temperature. Therefore, the dynamic behavior of the conductor's resistivity is related to and can be explored through the resisting distance (D).

Resisting Distance of Different Materials

The resisting distance (D) of a conductor is a common factor of the electrical resistivity indicated in Equation (35) and the lift energy for electrons to create currents in the conductor implied in Equation (23). The resisting distance term captures

the distinctions between insulators, conductors, and superconductors, which are explored next. However, as shown in Equation (24), the resisting distance is a sum of a large series, which makes it difficult to analyze. Fortunately, it can be easily demonstrated that this series converges quickly, even for an infinite series, because each term in the series converges to zero at the rate of $O(n^{-2})$. Each term in Equation (22) for $D_k(i)$ converges at the same rate as $O(n^{-2})$. Besides, we can also prove that the terms in $D_u(i)$ converge by reformulating Equation (19) as follows:

$$(36) \quad D_u(i) = \frac{2c^{i\%2}(R_b-r)}{(2iR_b+r)(2iR_b+R_b)} + \frac{2c^{(i+1)\%2}(r-R_b)}{(2(i+1)R_b-r)(2iR_b+R_b)}$$

where each term converges at the same rate as $O(n^{-2})$. Mathematician Leonard Euler proved the convergence of the infinite series in the Basel problem, specifically, $\Sigma(1/n^2) = \pi^2/6$. As a result, each term in the series converges to $C\pi^2/6$, where C represents the constant part in the term for particular values of c and R_b. Consequently, the sum of these terms converges for each tuple of c and R_b. This demonstrates that the model predicts a finite electrical resistance in a conductor, therefore requiring a limited amount of energy to raise electrons to the electron tunnels for current generation.

Analyzing the resisting distance using the entire series form in Equation (24) is challenging. As the influence on an electron from surrounding molecules decreases rapidly with distance, i.e., at the rate of $O(n^{-2})$, the first term d in the series should be significant enough for the analysis:

$$(37) \quad d = \frac{1}{r} + \frac{2c}{2R_b-r} + \frac{rc}{\left(2R_b-r\right)^2} - \frac{3c+1}{R_b}$$

Indeed, a numerical simulation indicates that the ratio of D/d converges rapidly and is bounded by a constant for any specific values of c and R_b. Thus, instead of working with the entire series of the resisting distance, we can just focus on the first term d of the series, which should be significant enough to provide insight into the entire series of the resisting distance.

Name	Symbol	Border Ra	Valence Ra	Resisting D (1/m)	Resistivity (m/MS)
Silicon	Si	210	111	5.37E+13	1.00E+03
Diamond	C	170	77	8.50E+11	1.00E+01
Aluminum	Al	125	118	1.87E+07	2.62E-02
Calcium	Ca	180	174	9.00E+06	3.45E-02
Iron	Fe	140	125	2.42E+08	1.00E-01
Copper	Cu	140	138	8.41E+05	1.69E-02
Platinum	Pt	175	128	1.50E+09	1.06E-01
Gold	Au	166	144	5.81E+07	1.61E-02
Mercury	Hg	155	149	3.49E+08	1.00E+00
	c = 0.1			Radius in pm	

Table 1, Resistivities of several materials compared with the resisting distances estimated using Equation (37). The Resisting D column shows the resisting distance (m^{-1}) for different materials, which are calculated using Equation (37), assuming a uniform value of $c = 0.1$. The values of R_v and R_b for each material are obtained from the ptable site. Specifically, the Valence Ra column used for R_v corresponds to the covalent radius, and the Border Ra column

for R_b is based on the Van de Waals radius or empirical radius for Ca, Fe, and Al. For simplicity, we did not include the common factor of property Z in the calculation.

First, let's explore the effect of R_v and R_b on the resisting distance. Equation (37) allows us to estimate the resisting distance for a conductor using its microscopic properties R_v and R_b, along with bond/attraction coefficient c. Unfortunately, the values for c are currently unavailable for most materials. To provide a rough range in this case, a uniform value of c = 0.1 is used to estimate the resisting distances for several materials. By using the values of R_v and R_b obtained from the ptable site, we calculated the corresponding resisting distances for these materials and compiled them in the Resisting D column of Table 1.

The results exhibit a strong correlation between the electrical resistivity (column Resistivity) and the resisting distance (column Resistive D), even using the uniform value of c = 0.1. The results should be more accurate if actual values for c are available for the evaluation. Notably, non-conductive materials such as silicon and diamond exhibit much higher resisting distances than metals. Theoretically, the electrical resistance of any material can be computed using Equation (35) as long as accurate values are available for the microscopic properties Z, R_v, R_b, and c. Nevertheless, these results demonstrate preliminary evidence to support the validity of the resistance distance model.

Now, let's examine the significance of the attraction coefficient c on resisting distance. The attraction coefficient characterizes the bond strength for the attraction between molecules. According to Equation (37), if there is no bond between molecules (i.e., c = 0) or the bond strength is weak (e.g., $c < \frac{1}{8}$), the resisting distance is always greater than zero, as indicated by the blue curve in Figure 5. It suggests the absence of electron tunnels, or disconnected tunnels, which could be the situation in insulators where bond strength is weak between certain molecules. Even though an electron may be ejected from its host atom with high energy, there are no fully connected tunnels for it to smoothly flow along.
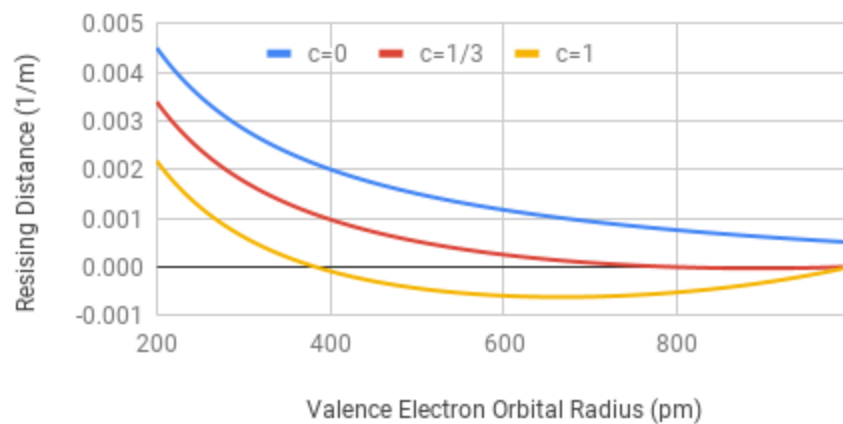

Figure 5, Resisting distance d (m^{-1}) for different values of c, calculated using Equation (37) with molecules placed 2000 pm apart and a fixed R_b = 1000 pm. The curves show that the resisting distance decreases as R_v increases towards R_b. The orbital radius at zero resisting distance is where the curves intersect the x-axis, denoted by R_c, indicating the starting point of entering the electron tunnel. The width of the electron tunnel increases with c. When c = 0, the resisting distance is always greater than zero, as indicated by the blue curve, suggesting that there is no

electron tunnel, which could be the case for insulators. A superconductor is a conductor with $R_v \geq R_c$, indicating that the valence orbital overlaps the electron tunnel.

Electron tunnels will develop in substances with high attraction coefficients (e.g., $c > \frac{1}{4}$). As c increases, the width of the electron tunnels increases accordingly. For instance, when $c = \frac{1}{3}$, there are small electron tunnels, as indicated by the red curve. When $c = 1$, the electron tunnels become wider, as shown by the yellow curve in Figure 5.

In normal conductors, electrons have to be energized into electron tunnels. The larger the gaps between valence orbitals and electron tunnels, the more energy is required to elevate valence electrons to the electron tunnels, and the higher the resistivity. This means that the resistivity of a conductor usually decreases with increasing c, as the gaps between electron tunnels and valence orbitals are typically small with wider electron tunnels. When electron tunnels are wide enough to overlap valence orbitals, valence electrons can enter and flow in the electron tunnels without lifting energy, eliminating resistance and achieving superconductivity.

Now, let's explore the condition of superconductivity. Because superconductors have no resistance, i.e., $\rho = 0$, with Equation (37), the superconductivity condition can be expressed as

$$(38) \quad \frac{1}{R_c} + \frac{2c}{2R_b - R_c} + \frac{cR_c}{\left(2R_b - R_c\right)^2} - \frac{3c+1}{R_b} = 0$$

where R_c denotes the conducting radius, which is the point where electron orbitals begin to overlap electron tunnels. In Figure 5, this is also the point at which the resisting distance curve intersects the x-axis, or the resisting distance becomes zero, i.e., $D = 0$. Thus, whenever $R_v \geq R_c$, superconductivity is achieved. By solving Equation (38) for R_c at different values of c, we found:

$$(39) \quad R_c \approx 0.382R_b \quad when \quad c = 1$$
$$\approx 0.621R_b \quad when \quad c = \frac{1}{2}$$
$$\approx 0.785R_b \quad when \quad c = \frac{1}{3}$$

The results imply that electrodrift or current may occur in an orbital well below the border. For instance, with $c = \frac{1}{2}$, valence orbitals will overlap electron tunnels when $R_v > 0.621R_b$, indicating the condition for superconductivity in this situation. The reason that electrodrift can take place below the border is due to the pulling from adjacent molecules. This typically occurs when the attraction between molecules is strong.

When $c = 1$, a valence electron experiences an attraction from an adjacent molecule equivalent to the force it would experience from its host molecule at the same distance. This scenario may occur when the adjacent molecule has an electron hole, which can occur after an electrodrift. This implies that if a valence electron is situated next to a molecule with an electron hole, it can drift to the next molecule without requiring additional lifting energy when the electron is at an orbital above 0.382 of the distance to the border. In a typical bond between molecules, $c < 1$. For example, when $c = \frac{1}{3}$, the electrodrift will occur at 0.785 of the border distance.

Therefore, the difference between insulators, conductors, and superconductors can be identified based on the solution to Equation (38). For a given material with a specific value of c, if the equation has no real solution, the material is an insulator. If real solutions exist, the material is either a conductor or a superconductor, depending on whether $R_v < R_c$ or $R_v \geq R_c$. Hence, the resisting distance model provides a quantitative mechanism to distinguish between them based on their microscopic properties.

Note that c represents the strength of a bond. Like molecular distance, bond strength is not fixed for a given substance but is a dynamic parameter influenced by pressure and temperature. Thus, a ceramic can become a superconductor under high pressure. This dynamic aspect will be explored next.

Dynamic Behavior of Electrical Resistivity

The resistivity of a conductor generally rises as temperature increases and falls as pressure increases. Conventional superconductors usually manifest at low temperatures, while high-temperature superconductors are often achieved at elevated pressures. These dynamic tendencies find explication within the framework of the tunnel theory we have formulated thus far.

As shown in Equation (35), the electrical resistivity of a conductor is proportional to the resisting distance at the microscopic scale. Therefore, the behavior of electrical resistivity is determined by the microscopic properties of c, R_v, and R_b, which are encapsulated in the resisting distance. These microscopic properties are dynamically influenced by pressure and temperature. Hence, insights into the dynamic behavior of electrical resistance can be gained by exploring the response of c, R_v, and R_b to the changes in pressure and temperature bridged through the resisting distance model expressed in Equation (24).

This dynamic behavior can be easily understood by analyzing the relationship between c, R_v, R_c, and R_b. The width of electron tunnels is determined primarily by the bond strength c. Therefore, for a given c, R_c positively relates to R_b. With a fixed molecular distance, represented by R_b, increasing the valence orbital radius, indicated by R_v, will reduce the gaps between R_b and R_v as well as between R_c and R_v, leading to a decrease in resisting distance and electrical resistivity, as shown by the curves in Figure 5. On the other hand, with a fixed valence orbital radius, reducing molecular spacing will also minimize the resistivity. The resistivity reduction in both cases is due to the decrease in $R_c - R_v$, representing the gaps between electron tunnels and valence orbitals. With this principle in mind, it becomes easy to understand the dynamic behavior of electrical resistivity related to the changes in pressure and temperature.

As pressure increases, the distance between molecules will be monotonically reduced, leading to a decrease in R_b. Without a change in the radius of valence orbitals (R_v), reducing R_b effectively diminishes the gaps between electron tunnels R_c and valence orbitals R_v therefore minimizing D and eventually resistivity. This highlights the intricate relationship between pressure and resistivity, which explains why resistivity decreases with increasing pressure and how many superconductors are achieved under high pressures, even at very high temperatures and for some insulators.

The reduction of molecular spacing will also induce various intermolecular forces, such as the development of compression bonds. This effect increases the attraction coefficient c. When c rises, the electron tunnel expands. The widening of

electron tunnels also reduces the gaps (R_c - R_v) between valence orbitals and electron tunnels and further diminishes the resisting distance and ultimately the electrical resistivity.

Other microscopic properties, such as electron orbital radius r, or more significantly the valence orbital radius R_v, are more sensitive to changes in temperature. As temperature rises, valence electrons become more excited and move to higher orbitals, causing R_v to increase. When there is enough pressure to confine the space between molecules, increasing R_v will reduce the gap between R_c and R_v, and therefore diminish D and resistivity. This elucidates why high-temperature superconductors can be obtained at high pressures.

However, as temperature increases in the absence of confining pressure, the increased repulsion of excited electrons between adjacent molecules pushes them apart, leading to an increase in R_b. Under normal pressure on Earth, which is relatively constant and weak compared to the repulsion between molecules at high temperatures, R_b typically rises faster than R_v, which in turn expands the gap between R_c and R_v. Consequently, D increases, as illustrated in Figure 6. This explains why the resistivity of a conductor typically rises with temperature increases and conventional superconductors achieved at low temperatures are usually destroyed at high temperatures.

When the temperature falls, electrons tend to retreat to lower orbitals, and repulsion between molecules weakens. The normal pressure on Earth becomes more dominant, creating a compression effect equivalent to increasing pressure. As R_b decreases, R_c is pushed lower faster than the reduction of R_v, minimizing the gaps between R_c and R_v and eventually causing valence orbitals to overlap electron tunnels. This explains the positive relationship between resistivity and temperature, and conventional superconductors achieved at low temperatures. In other words, the effect of lowering temperature is equivalent to increasing pressure.
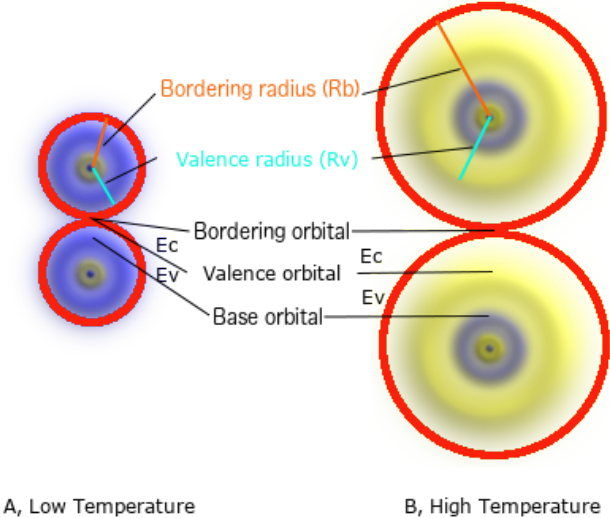

Figure 6, Transition of the electrical resistance phase. (A) Conventional superconductors are typically observed at low temperatures, where molecules are so close that the valence electrons can enter the electron tunnel without lifting energy, allowing electrodrift to occur freely. (B) As the temperature rises, molecules are pushed apart due to the increasing molecular repulsion caused by excited electrons at higher orbitals. The conducting radius increases faster than the valence orbital. Eventually, the valence orbital falls below the electron tunnel, destroying superconductivity.

In summary, the distance between molecules is influenced by pressure and temperature. Pressure plays the primary role in determining the molecular spacing, and temperature changes can create a similar effect to pressure. Molecular distances determine the gaps between electron tunnels and valence orbitals and influence the induction of intermolecular bonds. The bond strength also controls the width of electron tunnels, affecting the gaps between valence orbitals and electron tunnels. These gaps correlate with resistivity in conductors, while there is no such gap in superconductors. The bond strength is also the primary factor that distinguishes insulators from conductors. Therefore, the resistance state of matter is dynamically determined by both pressure and temperature.

So far, the electron tunnel theory provides a unified framework for understanding the dynamic nature of insulators, conductors, and superconductors. In the next few sections, let's apply this theory to explain the phenomena observed in superconductors.

The Cause of the Meissner Effect

A superconductor is not just a perfect conductor but is more significant because of the Meissner effect, in which an external magnetic field is expelled from the superconductor during the transition to the superconducting phase.[9] It is important to note that a magnetic field created by induction requires a change in magnetic flux based on Faraday's law of induction.[20-21] The Meissner effect is observed during the transition to the superconducting phase in the presence of an existing magnetic field, where there is no change in magnetic flux.

In a normal conductor, there is no current because valence electrons are below electron tunnels. After the transition to the superconducting phase, valence orbitals overlap electron tunnels. Valence electrons can enter the electron tunnels and flow across molecules without lifting, resulting in resistance-free currents, i.e., superconductivity. The internal magnetic fields induced by these random currents cancel each other locally. However, in the presence of an external magnetic field, the directions of the currents are deflected by the Lorentz force:

$$(40) \quad F = q(E + v \times B)$$

where q represents the electrical charge, v is the velocity of the charge, B is the magnetic field, E is the electric field, and F is the force exerted on the charge.[22-24] When observing along the direction of the applied magnetic field, a moving electron is deflected and circulates in a clockwise direction, resulting in a magnetic field. This field counteracts the applied magnetic field inside the superconductor and reinforces the applied field outside. The net result appears as if the applied field were expelled from the superconductor.

In both the Meissner effect and normal Faraday's induction, the magnetic fields are generated by the flow of charges deflected by the Lorentz force. Thus, the Meissner effect is also related to induction. The primary difference lies in the fact that random currents naturally exist in superconductors due to valence electrons being present within electron tunnels. In contrast, there is normally no current in conductors, and electrons must be raised to electron tunnels to create currents. During a normal Faraday's induction, electrons are elevated by a change in the magnetic flux. However, due to the resistance in conductors, the inducted currents are not sustainable. Induction also varies in superconductors when the

external field changes. Since resistance is zero in superconductors, the induced currents can fluctuate to compensate for the external field, up to a certain extent limited by the critical current density discussed next.

The Limit in Critical Current Density

The critical current density refers to the maximum current density that a superconductor can tolerate. According to Stefan Boltzmann's law, the radiation power P emitted by a blackbody is directly proportional to the fourth power of its absolute temperature T:

$$(41) \quad P = pT^4$$

where p is the Stefan-Boltzmann constant. This law can also be derived by integrating Planck's law over the frequency and then over the solid angle. At equilibrium, the rate of energy absorption of a body is equal to the emission.[14] Therefore, the body also absorbs energy from surroundings at a rate proportional to the fourth power of the temperature. The current density in a body, such as in a superconductor, corresponds to the density of electrodrifts. Each electrodrift starts from an electron excitation as a result of energy absorption. The electron's energy of superconductors is absorbed from the environment given by Equation (13). Consequently, the electrodrift/current density should be also proportional to the fourth power of its temperature. By introducing a conversion efficiency C, the current density can be expressed as

$$(42) \quad J = CT^4$$

where C is a property specific to a superconductor. This equation indicates that the maximum current density of a superconductor is proportional to and limited by the fourth power of the temperature, meaning that the critical temperature determines the critical current density of the superconductor. This explains why conventional low-temperature superconductors typically have lower critical current densities when compared with high-temperature superconductors.

Critical Magnetic Field Limited by Critical Current Density

When subjected to an external magnetic field, a superconductor will lose its superconductivity once the applied field exceeds a certain intensity, known as the critical magnetic field. At low intensities, an external magnetic field is expelled from a superconductor in the Meissner effect. As the intensity of the external field rises, the internal field increases accordingly to counteract the applied field.

The internal field of a superconductor arises from counter-currents inside the superconductor, and the field intensity correlates to the density of the counter-currents. As suggested in the last section, there is a limit to the maximum current density in a superconductor at a specific temperature. Beyond the critical current density, the external field is no longer fully canceled inside the superconductor, and the applied field cannot be entirely expelled in the Meissner effect.

Once the critical current is exceeded, the moving charges, including the orbital electrons, are deflected by the Lorentz force in the remaining external field. The orientation of electron orbitals surrounding each atom is deformed in a way that

the electron clouds are compressed along the direction of the applied field or flattened perpendicular to the direction of the applied field, as illustrated in Figure 7B. Valence electrons play a significant role in superconductivity and are affected the most due to less tangling effect from other electrons in the host atom. When the applied field is over the critical field, the valence electrons will withdraw from the electron tunnels, destroying the superconductivity.
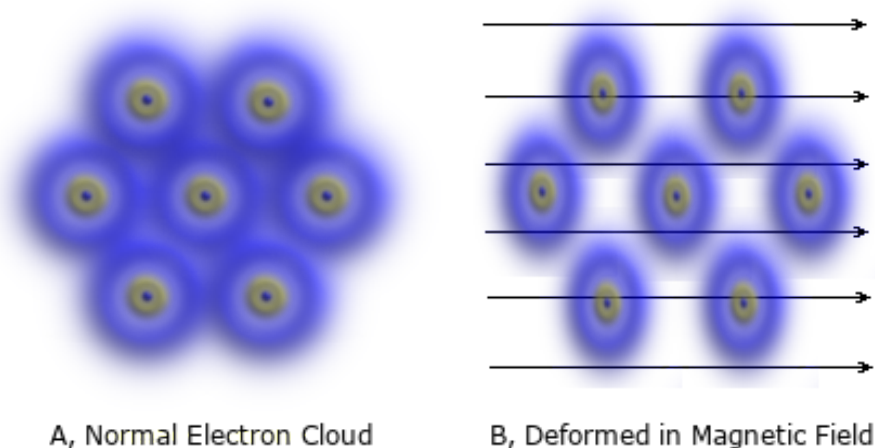

A, Normal Electron Cloud   B, Deformed in Magnetic Field

Figure 7, Superconductivity destroyed in a magnetic field over a critical intensity. (A) In a weak or absence of an external magnetic field, the applied field can be completely canceled by the internal field in a superconductor due to the Meissner effect. The electron clouds of valence electrons extend normally into electron tunnels. Superconductivity may withstand a magnetic field up to a critical intensity. (B) However, an external field over the critical intensity cannot be completely offset due to the limit of critical current density. Orbital electrons are deflected by the Lorentz force in the remaining field and divert their orbiting plane in the direction perpendicular to the external field. This action compresses the electron clouds like squashed lanterns. The deformation of orbitals causes the valence electrons to withdraw from the electron tunnels, destroying superconductivity.

Therefore, the failure of superconductivity above the critical magnetic field is due to the limit of critical current density. As predicted by Equation (42), a higher temperature corresponds to a higher critical current density. Higher critical current density, in turn, sustains a higher critical magnetic field. This explains the strong correlation observed between critical temperatures and critical magnetic fields.

Molecular Structure Determining Type-II Superconductor

A type-II superconductor exhibits at least two critical fields: B_{c1} and B_{c2}.[25-27] Normal superconductivity is observable in an applied magnetic field below B_{c1}. The superconductivity is destroyed at a field intensity over B_{c2}. Between the two fields, the superconductivity is partially destroyed in certain regions of the superconductor. These non-superconductive islands are known as magnetic vortices. The density of the vortex increases as the intensity of the applied magnetic field rises. Type-II superconductors are usually made of alloys or compounds.

Figure 8 illustrates the crystal structure of a type-II superconductor composed of two distinct types of molecules. Normal superconductivity is observable in a magnetic field $B < B_{c1}$, as shown in Figure 8A. This occurs because the applied field is

below the critical fields for all molecules, and every molecule is superconducting. Superconductivity is destroyed in a field $B > B_{c2}$, as illustrated in Figure 8C. B_{c2} represents the maximum critical field for all materials in the superconductor, and when the field exceeds B_{c2}, superconductivity is destroyed for every type of material.
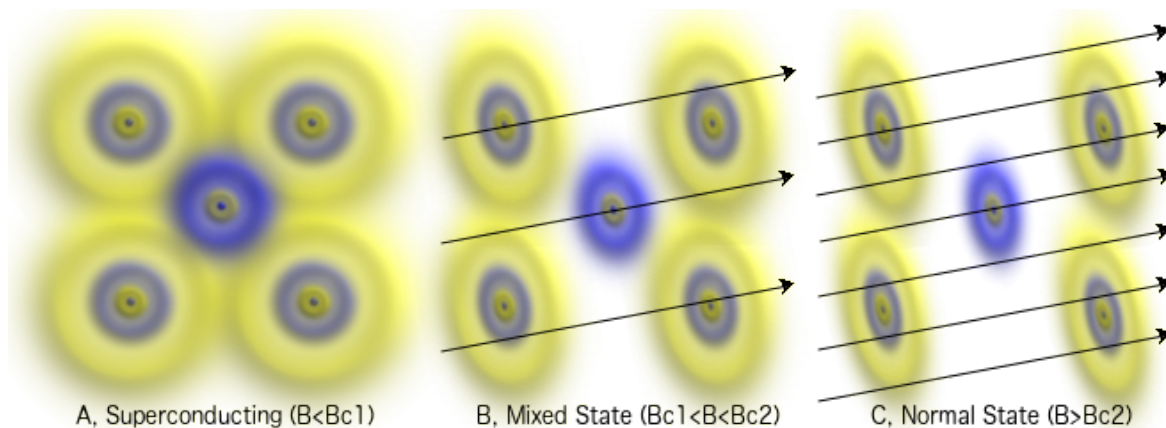

A, Superconducting (B<Bc1)   B, Mixed State (Bc1<B<Bc2)   C, Normal State (B>Bc2)

Figure 8, Responses of a type-II superconductor to different intensities of external magnetic fields. (A) In a magnetic field below the minimum critical intensity, electron tunnels between all molecules are fully connected, and superconductivity is maintained entirely. (B) In a field between the minimum and maximum critical intensities, some valence orbitals separate from the electron tunnels, such as the small molecule at the center, resulting in vortices or superconducting holes in the mixed state around the small molecules. (C) Under a field above the maximum critical intensity, the superconductivity is destroyed as all the valence orbitals withdraw from the electron tunnels. Additionally, note that the deformation of the electron clouds is affected by the direction of the applied field, which explains why the critical fields of a type-II superconductor may vary depending on the direction of the external field.

In a field between B_{c1} and B_{c2}, as depicted in Figure 8B, the superconductivity for the central molecule is destroyed while other molecules surrounding it remain superconductive. The center part becomes a non-superconductive island, corresponding to the magnetic vortex which allows the magnetic flux to penetrate for flux pinning effect.

The crystal structure of type-II superconductors typically has different arrangements of molecules in various directions, especially with compounds. Magnetic fields applied in various directions may cause diverse deflection/flattening effects on the electron clouds. Consequently, superconductivity may be destroyed at different field intensities depending on the direction of the applied field. This effect is also illustrated in Figure 8. Two critical magnetic fields are observed with an external field applied at a small angle. Different critical fields may be observed with a field applied from another direction. As the geometry of the deformed electron clouds changes with the direction of the applied field, the valence electrons may withdraw from the electron tunnels at different field intensities in various directions. For instance, the superconductivity of YBCO can withstand an external magnetic field of up to 250 T when aligned parallel to the CuO_2 planes, or the a-b plane of YBCO crystals.[28] However, the superconductivity is destroyed by an external field of 120 T when aligned perpendicular to the CuO_2 planes, or along the c-axis direction of the crystals.

The destruction of superconductivity is caused by the withdrawal of valence orbitals from electron tunnels under the influence of a magnetic field. This effect can be related to specific bonds and may vary depending on the field's direction. Type-II superconductors are typically composed of alloys or compounds, where each type of molecule can form one or

more bonds with adjacent molecules in various directions. Consequently, the more complex the molecular structures in a superconductor, the greater the variations in the critical destruction fields.

The molecular structure of compounds is often asymmetrical due to various bonds in different directions. Consequently, the structure of electron tunnels also varies with direction, resulting in different critical fields in various orientations. The two critical fields frequently mentioned in the literature likely represent the minimum and maximum of all the critical magnetic fields present in a type-II superconductor. In the mixed state, vortices form in regions where superconductivity is partially destroyed. As the intensity of the applied magnetic field increases and various critical fields are successively exceeded, the vortex density increases.

Correlation between Superconductor, Density, and State of Matter

According to the proposed theory, superconductivity arises from the overlap between valence orbitals and electron tunnels, which is associated with smaller molecular spacing and, consequently, higher density. Thus, the theory predicts that superconductivity is more likely to be found in high-density elements. This prediction aligns well with the superconductive elements found in the periodic table. Figure 9 highlights known superconductive elements in blue boxes, which correspond well with the high-density elements shown in Figure 10.
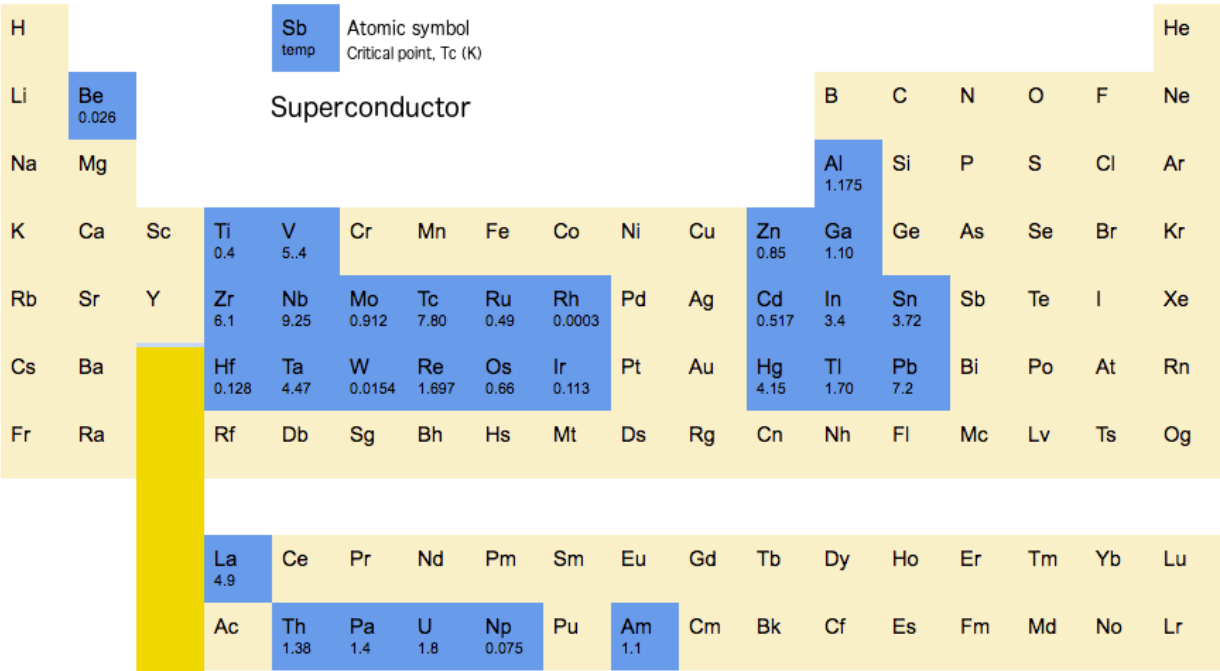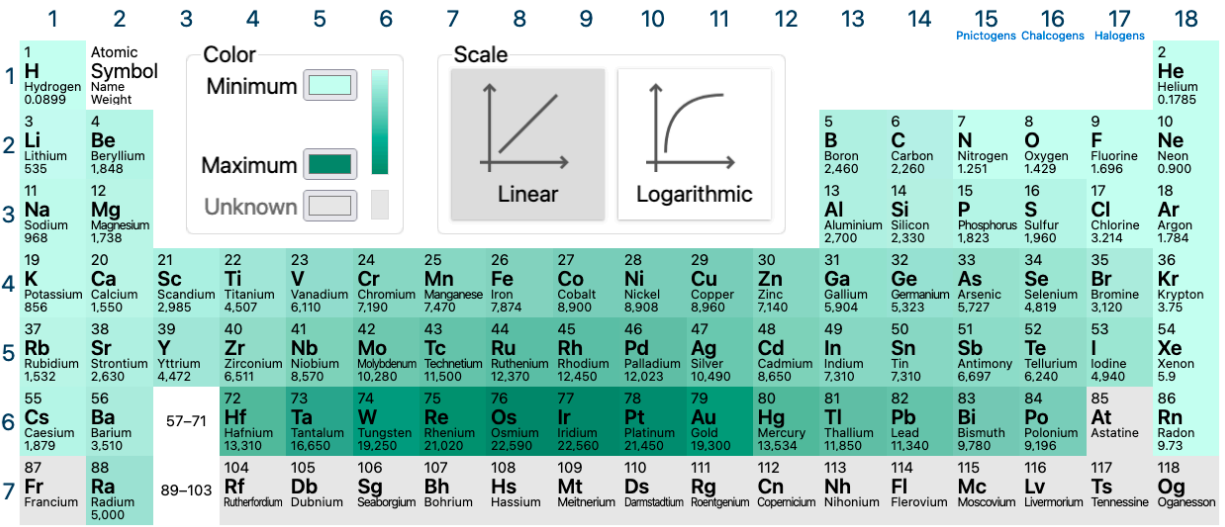

Figure 9, Known superconductive elements (T_c from Peter J. Lee's page).

Figure 10, The densities of elements (screenshots from ptable site).
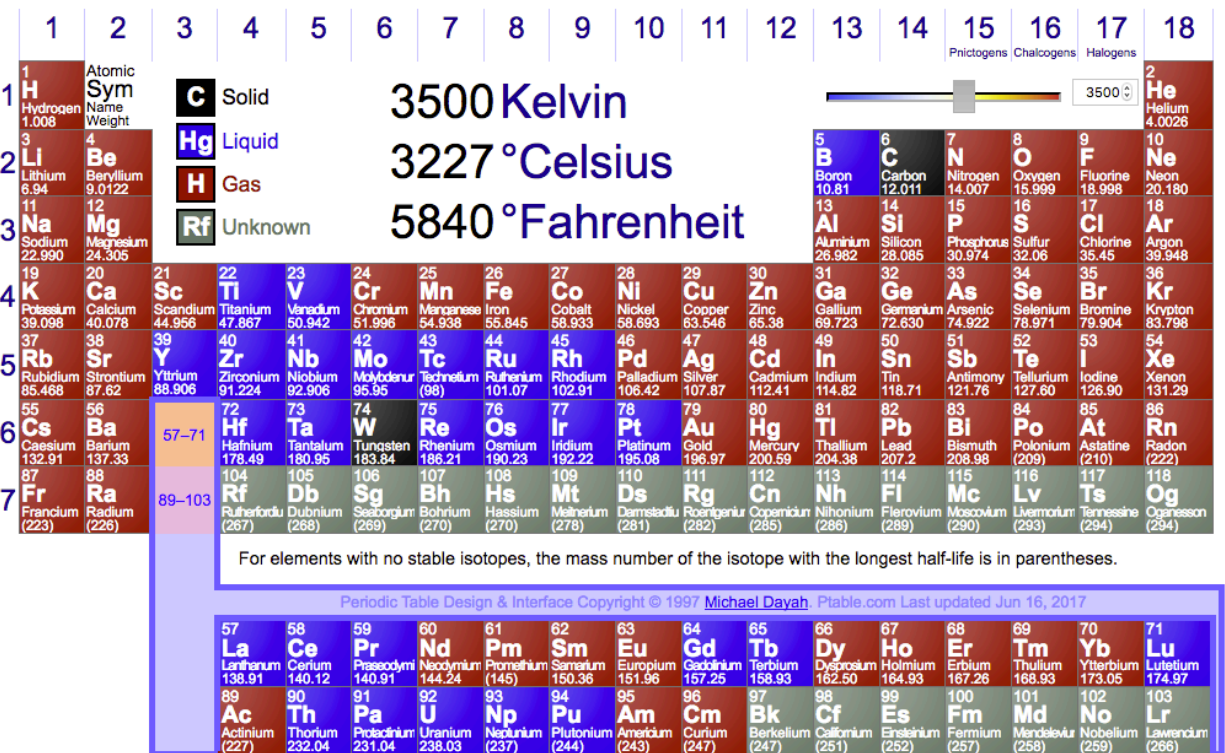
Figure 11, The states of elements at 3500 K (screenshots from ptable site).

Highly repulsive molecules are likely to push each other apart, resulting in larger molecular distances and a greater tendency to become gaseous. In contrast, smaller molecular spacing is typically associated with less repulsion between molecules, leading to lower volatility and higher melting and boiling points. Therefore, the theory also predicts that superconductive elements correlate with elements having high boiling points, a prediction also supported by observations. Figure 11 highlights elements that remain in the solid or liquid phase at 3500 K, which corresponds well with the superconductive elements shown in Figure 9.

Electrodrift Explanation of Flux Quantization

Magnetic flux measures the total magnetic field passing through a given area. A looping current generates magnetic flux, and the smallest unit of flux is created by a single electron circulating an area, making magnetic flux quantized. The value of the flux quantum Φ_0 can be determined by applying gauge transformations to the Schrödinger equation. Although the phase of the wave function depends on the gauge, the physical predictions do not, allowing us to conclude that the value of Φ_0 is a gauge-invariant quantity:

$$(43) \quad \Phi_0 = \frac{h}{2e}$$

where both h and e are fundamental physical constants for the Planck constant and the charge of an electron, respectively. This prediction may be validated using a superconductor in a donut shape.

Based on the proposed theory, currents or electrodrifts in a superconductor originate from electron orbital transitions. An electron jump simultaneously creates an excited electron and an electron hole behind it. The drifting of these charges results in a flow of negative charge and another of positive charge. The minimum flux is produced by the two flows moving in opposite directions around a donut-shaped superconductor, which is equivalent to two electrons traveling in the same direction around the donut. Consequently, the theory predicts the minimum flux in a donut-shaped superconductor to be twice the flux quantum Φ_0. This prediction is confirmed experimentally by B. S. Deaver and W. M. Fairbank,[29] and independently by R. Doll and M. Näbauer.[30

Prediction of Electrical Resistance State of Matter

As discussed previously, the dynamic behavior of electrical resistivity is influenced by pressure and temperature. This implies that materials can transition between insulating, conducting, and superconducting phases. For instance, insulators can become superconductors under sufficient pressure, as observed in many high-temperature superconductors. Mercury, which is a conductor at normal temperatures, transitions to a superconductor at low temperatures. Just as the state of matter can transition from solid to fluid, the proposed theory predicts that the electrical state of matter can also transition between insulating, conducting, and superconducting at different pressures and temperatures.

The electrical phase transition of matter is related to the presence and connectivity of electron tunnels between molecules. The characteristics of electron tunnels are determined by the attraction/bond coefficient between molecules, which is determined by pressure and temperature. Therefore, electrical phase transitions result from changes in pressure and

temperature and can be represented in a phase diagram with transition boundaries, similar to phase diagrams for states of matter.

Pressure influences electrical phase transitions through two key factors: molecular spacing and bond strength. Increasing pressure reduces the distance between molecules, inducing bonds between them. This reduction in molecular spacing decreases the gaps between electron tunnels and valence orbitals, thereby minimizing resistivity and potentially achieving superconductivity. At closer distances, electron clouds are influenced by adjacent molecules, causing them to redistribute and form new bonds.

As illustrated in Figure 12, the width of electron tunnels increases with rising bond strength, represented by the attraction coefficient, which typically reduces the gaps between electron tunnels and valence orbitals. Both of these effects facilitate the transition of the electrical phase from insulating to conducting and/or superconducting. Additionally, as discussed earlier, decreasing temperature has an equivalent effect to increasing pressure by causing compression. Therefore, the electrical resistance state of matter can transition from one phase to another in response to changes in pressure and/or temperature.
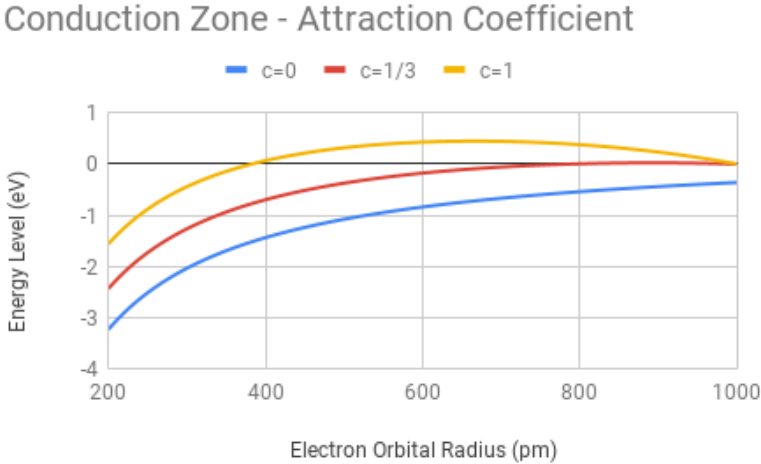

Figure 12, Relationship between electron tunnel width and intermolecular bond strength influenced by the attraction coefficient c using a model of two molecules 2000 pm apart. Each curve indicates the energy level of an electron as a function of the electron orbital radius for a specific attraction coefficient, calculated using Equation (23) with a fixed R_b of 1000 pm. The x-axis starts at a molecule center and extends toward the adjacent molecule to the right. The figure plots only a section on the left half of the two molecules. The electron energy level rises as the orbital radius increases from the molecule center to the border. When $c = 1$, the energy level elevates from negative values, turning positive at a radius of 382 pm, as illustrated by the yellow curve. A positive energy level indicates the electron is no longer confined by its host nucleus and can flow between the molecules. Thus, the region of the positive energy level represents the electron tunnel. Note that with $c = 1$, the curve simulates the attraction from the next molecule with an electron hole, creating the widest electron tunnel. When $c = \frac{1}{3}$, the energy level turns positive at a radius of 785 pm, resulting in a narrower electron tunnel, as shown by the red curve. When $c = 0$, the energy level remains entirely negative, indicating no electron tunnel, as illustrated by the blue curve.

For a conventional superconductor, the critical point typically refers to the transition temperature observed at normal pressure on Earth. However, multiple critical temperatures may be observed at different pressures for the same material. Each critical temperature represents a point on the superconducting transition boundary at a specific pressure. Collectively, these critical points depict the superconducting transition boundary in a phase diagram, as illustrated by the blue curve in Figure 13.
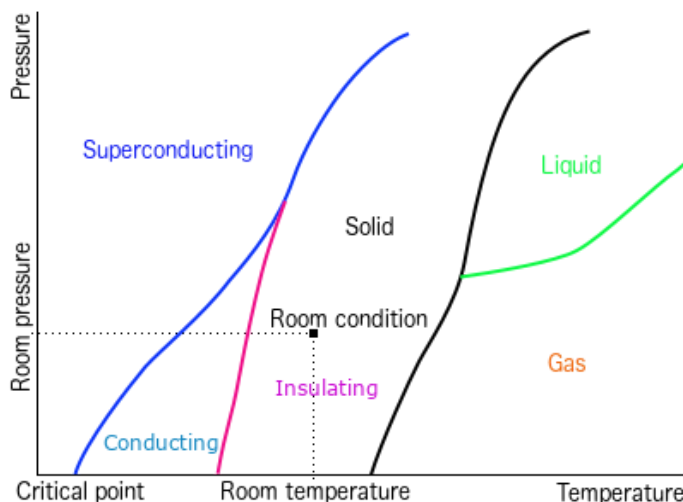

Figure 13, Electrical resistance phase diagram depicting superconducting, conducting, and insulating transition boundaries, along with the transition boundaries of conventional shearing resistance states. The transition boundary for superconductivity is the curve connecting all the tuples of critical temperatures and pressures of the superconductor. For most substances, this boundary typically resides on the high-pressure and low-temperature side of room conditions, which explains why room-temperature superconductors are less common due to unfavorable conditions on Earth. The overlap between insulating and superconducting transition boundaries indicates there is a direct transition from insulators to superconductors.

The transition boundary can also be theoretically determined using the resisting distance model. Equation (35) can be interpreted as a 3D surface representing resistivity over the domains of pressure and temperature. The transition boundary appears as a curve on the pressure-temperature plane where the surface intersects the plane at zero resistivity, as described in Equation (38), i.e., at $\rho = 0$. The solution to Equation (38) can be expressed in the form of

$$(44) \quad R_c = f(c, R_b)$$

where each term of $R_c(t,p)$, $R_b(t,p)$, and $c(t,p)$ is a function of temperature t and pressure p. Equation (38) does not always have a real solution. This likely occurs when the intermolecular attraction is weak, e.g., $c < \frac{1}{6}$, which corresponds to the insulating phase. However, when it does have a real solution for a given c, all the points of (t,p) on the solution (44) define the transition boundary between the conducting and superconducting phases. Any point (t,p) with $R_v(t,p) > R_c(t,p)$ must be on the superconducting side, while points with $R_v(t,p) < R_c(t,p)$ are on the conducting side. For instance, a real solution to Equation (38) at $c = 1$ is:

$$(45) \quad R_c = \frac{3-\sqrt{5}}{2}R_b$$

$$\approx 0.382R_b$$

In this case, the material will exhibit superconductivity whenever the condition of pressure and temperature extends the valence orbital to a radius of 0.382 or greater of the distance to the border. Otherwise, it will behave as a conductor.

Since the decrease in temperature has an effect equivalent to the increase in pressure, the transition boundary should generally trend from low pressure and temperature toward high pressure and temperature, as illustrated by the blue curve in Figure 13. This determines why high-temperature superconductors are typically obtained under high pressures.

For conductors, the difference between $R_c(t,p)$ and $R_v(t,p)$ represents the gap between electron tunnels and valence orbitals, which is proportional to electrical resistivity. A large difference between $R_c(t,p)$ and $R_v(t,p)$ indicates more energy is required to raise the valence electrons to the electron tunnels, therefore higher resistivity.

The electron tunnels in an insulator cannot connect into a continuous network when the bonds between certain molecules are so weak that the attraction coefficient is less than 0.225. Therefore, all the points *(t,p)* on the temperature-pressure plane where *c(t,p)* = 0.225 define the insulating boundary, as illustrated by the purple curve in Figure 13. This boundary should be to the high-temperature side of the superconducting boundary. There may be overlaps between superconducting and insulating boundaries. If there is an overlap, the overlap is the portion of the transition boundary from insulating to superconducting directly. A triple transition point may also exist in an electrical resistance phase diagram, as illustrated in Figure 13 at the point when the purple curve intersects with the blue curve.

The prediction of electrical phase transition is supported by the observed behavior of conductors and superconductors in response to changes in pressure and temperatures. For instance, the critical temperature of H_2S superconductors increases with pressure, ranging from 23 K at 100 GPa to 150 K at 200 GPa.[31] The transition boundaries of many materials can be measured or validated in most high-pressure laboratories, given the right equipment and expertise.

Despite being predicted to be an ordinary state of matter, superconductors are not as common as conductors on Earth because the standard conditions of pressures and temperatures on Earth are not favorable for superconductivity. However, Superconductivity is theoretically expected to be more common under high pressures. So, superconductors should prevail inside large planets, which might be responsible for the origin of the planet's magnetic fields. This may explain why the planet's magnetic fields are popular in large planets. As a consequence, a hypothesis has been proposed that the geomagnetic field originated from superconductors inside Earth.[32]

Synthesizing Room-Temperature Superconductors

The elegance of the proposed theory lies in its ability to provide a unified framework for understanding insulators, conductors, and superconductors, and more importantly, in offering practical guidelines for synthesizing superconductors. By comprehending the microscopic basis of superconductivity, the synthesis of room-temperature superconductors is no longer a random endeavor but becomes a deliberate engineering task. For practical applications, it is essential for superconductors to function under normal Earth conditions. The main challenge in achieving superconductivity is the repulsion between molecules, which intensifies as the temperature rises, especially for symmetrical molecules. The key

strategy in synthesizing superconductors is to compress the spacing between molecules. Pressure not only reduces molecular distances but also promotes bonding between molecules, both of which are critical for achieving superconductivity. The following principles can significantly narrow the search for room-temperature superconductors:

- The engineering strategy should leverage molecular attractions to counteract repulsions between molecules instead of replying to external pressures. By designing the molecule structures to induce attractive forces between specific atoms, it should be feasible to bring together certain atoms into proximity, facilitating their valence orbitals to extend into the electron tunnels and therefore achieving superconductivity.
- Electronegativity[33] plays a significant role in the choice of elements for synthesizing superconductors. It is important to avoid elements with extremely high electronegativity, as they would strongly retain electrons, hindering the flow of electrons across molecules. Conversely, elements with too weak electronegativity may be insufficient to establish the necessary intermolecular attractions needed to develop wider electron tunnels. It is advantageous to choose elements in a narrow range of electronegativities. By maintaining a close range of electronegativities among the selected elements, it becomes possible to strike a balance that promotes the formation of interconnected electron tunnels.
- The connectivity of electron tunnels is also critical for superconductivity. Excessively complex and large compounds have the potential to disrupt the continuity of electron tunnels. Connected electron tunnels should be at the same potential/energy level. In a crystal made of complex molecules, the field intensities between different regions are likely uneven, as in most insulators, which may disrupt the continuity of electron tunnels.
- The molecular structure of compounds or alloys that incorporate a combination of large and small atoms gives rise to uneven intermolecular tensions, thereby increasing the likelihood of fostering compressions between certain atoms and the development of electron tunnels. A smaller atom may pull in nearby atoms, introducing compression between certain atoms that can facilitate the development of wider electron tunnels to overlap valence orbitals.

Summary

The challenges encountered by conventional theories when attempting to account for the phenomena of resistivity and superconductivity under high pressures prompt us to realize the flawed presumptions at a deeper foundational level. These misapprehensions might be a contributing factor to the prolonged inability to fully comprehend the mechanisms of superconductivity and to search or synthesize room-temperature superconductors. By departing from these fallacies, an avenue opens to formulate an alternative theory.

The proposed theory provides insight into resistivity and superconductivity at the microscopic scale while offering a comprehensive explanation of the properties and phenomena of conductors and superconductors. Its prediction of electrical resistance states of matter provides a unifying framework that connects different electrical states through the concept of electron tunnels predicted in the models. Superconductivity is an ordinary state of matter in this framework, although it is not commonly observed in normal conditions on Earth.

The significance of this theory lies in its provision of practical guidelines for engineering room-temperature superconductors. Most superconductors to date have been obtained under extreme conditions, such as low temperatures or high pressures, which are impractical for many applications. To achieve room-temperature superconductivity, we need to take a different approach. This involves designing molecular structures that can harness molecular attraction to overcome

the repulsion and bring molecules closer. This strategy would eliminate the need for external pressure and make it possible to achieve superconductivity under ordinary conditions on Earth.

Acknowledgments

See Also

- [Is There a Sea of Free Electrons in Metals?](#) [(PDF)](#)
- [Unified Theory of Low and High-Temperature Superconductivity](#) [(PDF)](#)
- [Superfluids Are Not Fluids](#) [(PDF)](#)
- [Electron Tunnel](#) [(PDF)](#)
- [LK-99 Limitations and Significances](#) [(PDF)](#) [(中文)](#)
- [The Cause of Brownian Motion](#) [(PDF)](#)
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Revision History

- [06/02/2019: Uncovering the Mystery of Superconductivity](#)
- [06/16/2019: Unified Theory of Resistivity and Superconductivity](#)
- [06/18/2021: Unified Theory of Superconductors and Conductors](#)
- [09/08/2022: Unified Theory of Low and High-Temperature Superconductivity](#)
- [09/18/2022: Added Sections for Flux Quantization and Isotope Effect](#)
- [10/08/2022: Added Superconductivity Energy, Critical Current, and Overcooling Effect](#)

- [10/14/2022: Added Sections for Electrodrift and Superconductivity](#)
- [10/18/2022: Introduced Resistivity Model and Resistive Distance](#)
- [01/16/2023: Added Compression Bond, Conducting Radius, and Conduction Zone](#)
- [01/24/2023: Restructured the Sections and Clarified Concepts and Terms](#)
- [05/18/2023: Improved Clarity and Renamed some Sections](#)
- 05/24/2024: Supported by Study of Known Superconductors

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