# Unified Theory of Low and High-Temperature Superconductivity

Liu, Jerry Z. Ph.D. ZJL@CS.Stanford.EDU Stanford University, California

#### Abstract

Superconductors pose great promise for applications. Over the last century, substantial search efforts failed to find practically valuable, room-temperature superconductors. Meanwhile, the popular Bardeen-Cooper-Schrieffer theory for superconductivity is also facing challenges as it cannot justify the high-temperature superconductors discovered recently. The root problem might be in the traditional model for electrical resistance, suggesting the cause of the resistance is due to particle collision of electron flow in conductors. An alternative theory is proposed in this study. Under pressure, molecules are packed closely. Electron clouds in molecules adjust to adjacent molecules. The uneven distribution of electrons results in compression bonds. So, the distance between molecules may be so small that the valence electrons are close or even at the border between molecules. An electron may drift along borders and switch from one molecule to the next. A series of electron drifts results in a current. The attraction between electrons and nuclei is the primary cause of electrical resistance. To create currents in conductors, energy is needed to lift valence electrons to the borders. The distance between molecules determines the lifting energy, which is proportional to the resistivity. Intermolecular distances result from a balance between intermolecular attraction and repulsion and are also subject to changes in temperature and pressure. Hence, the resistivity of a conductor correlates to the temperature and pressure. For instance, the distance between molecules can be reduced by increasing the confining pressure. This explains why resistivity decreases as pressure increases and high-temperature superconductors are mostly obtained at high pressures. Superconductivity is just a state of matter at certain combinations of temperatures and pressures when the distance between molecules is so small that allows valence electrons to drift from one molecule to the next without the need for lifting energy. Hence, there is no resistance. This theory not only unifies the cause of resistivity for both conductors and superconductors but also superconductivity at low and high temperatures. Based on this theory, a mathematical model has been constructed that predicts and explains the properties and phenomena of superconductivity. Intermolecular repulsion is the primary hurdle to superconductivity. Based on these understandings, promising hints are provided to expedite the search for room-temperature superconductors.

## Introduction

Initially discovered in 1911, superconductivity has been a hot research subject due to its extraordinary properties and promising applications.<sup>[1-2]</sup> Cooper pairs of electrons bound together at low temperatures were proposed to be responsible for superconductivity in Bardeen-Cooper-Schrieffer (BCS) theory.<sup>[3]</sup> Since 1986, more and more superconductors have been obtained at higher and higher temperatures, substantially above the theoretical maximum prediction based on BCS theory.<sup>[4-8]</sup> Most high-temperature superconductors are obtained under high pressures. BCS theory cannot account for the positive effect of pressure on superconductivity and is inadequate to explain many phenomena observed in superconductors, such as the Meissner effect.<sup>[9]</sup>

Meanwhile, the traditional model for electrical resistance also faces a similar challenge. Most modern theories can trace their origins back to the Drude model, which suggests electrical resistance is caused by collisions between flowing electrons and the crystal lattice in conductors.<sup>[10]</sup> Each collision scatters the electron flow and dissipates some of the electron's energy, resulting in electrical resistance. If the Drude model were correct, one would expect high-density materials to be more resistive. As confining pressure increases, molecules are packed more densely in conductors, increasing the chances of collisions and resulting in higher resistivity. However, observations indicate just the opposite.<sup>[11-13]</sup>

The failure of the theories at high pressures for both conductivity and superconductivity may not be coincidental but a consequence of the implicit assumption in the collision model for resistivity. This might be the misleading concepts that impede and limit progress both in theory and practice. Rather than treating conductivity and superconductivity in different models, we believe both should share the same physics mechanism. Following Occam's razor principle, we proposed a simple theory postulating that resistivity is positively related to the distance between molecules in conductors. Intermolecular distance is affected by and changes dynamically with temperature and pressure. So, the resistivity of conductors also correlates to the temperature and pressure.

Throughout the next few sections, we will start with basic concepts to build up the theory. With some simplifications, a model is constructed based on the proposed theory to provide a quantitative explanation for the observations in both superconductors and conductors. The model also predicts that superconductivity is an ordinary phase for any matter and is common at high pressures. The theory and model not only reveal the face to tackle the problem in the search for room-temperature superconductors but also provides some hints and guidelines for us to conquer the problem effectively.

# The Dynamics of Electron Orbitals

Based on Planck's law and observations of radiation and absorption spectrum patterns, Niels Bohr postulates an electron in an atom only carries a certain discrete energy, therefore must be at an orbital corresponding to the energy level. The Pauli exclusion principle states that no two electrons in an atom can share the same four quantum numbers. Each orbital in an atom is characterized by three quantum numbers corresponding to electron energy, angular momentum, and magnetic momentum. These are the major physics that determine electron orbitals in atoms that each such orbital can only be occupied by at most two electrons. These two electrons must differ in their spin. Hence, electrons must spread in different orbitals around an atom.

Electrons are attracted to their nuclei by Coulombic force and tend to retreat to low orbitals. The **ground state** of an atom is the state where all the electrons occupy a set of orbitals at the lowest possible energy levels. After absorbing some energy, such as from radiation or electromagnetic fields, an electron in an atom will excite and jump to an orbital at a higher energy level. Any matter at a temperature above 0 K has some excited electrons. An excited atom will miss some electrons in its ground orbitals. In other words, there are **orbital/electron holes** in the ground orbitals. On the other hand, an excited electron is not stable and tends to retreat into orbital holes at low energy levels after emitting some photons, which releases some of its energy absorbed previously.

Electrons of an atom are dynamically cycling through the two above processes simultaneously. A single electron constantly gains and loses energy, while changing its orbital level from low to high and high to low. In these processes, an atom constantly exchanges energy with its environment. If the temperature of the atom is higher than the environment, the energy exchanges will not be at the same rate. The direction of the net energy flow will be towards the environment. The temperature of the atom decreases, eventually to a point where the energy flow becomes even in both directions. This is the **equilibrium state** of the atom in that environment. The outermost orbital of excited electrons is called the **valence orbital**. The valence orbital in an atom rises and falls dynamically as temperature changes.<sup>[14]</sup>

# **Compression Bonding**

Electron orbitals are subject to the influence of nearby electromagnetic fields. Unlike in isolated atoms, restricted by adjacent atoms in bulk materials, electrons adjust the clouds and redistribute unevenly, inducing local fields, such as London dispersions<sup>[15]</sup>, and resulting in different forces and bonds between atoms and molecules. Compression bonding is one of the intermolecular forces predicted in a study of superfluidity.<sup>[16]</sup> Under pressure, helium molecules are squeezed together. In response to the repulsions of the electrical fields from adjacent molecules, the electron cloud of each molecule shrinks along the axis of the two protons. The uneven distribution of electron density in different directions creates local fields: positive on the axis of the protons and negative on the plane perpendicular to the axis. An attraction arises from the distorted electron fields. Driven by this force, the molecules reorient themselves to minimize

their potential energy. The molecules eventually stabilize at a low potential layout as shown in Figure 1B, resulting in compression bonding between them.



Figure 1. Formation of compression bonding. Under normal pressures, superfluids can be obtained from liquid helium by reducing the temperature. Solid helium cannot be produced by further decreasing the temperature because there are no attractions to hold the molecules together. Under high pressures, the electron cloud of each molecule shrinks along the axis of the two protons. The uneven distribution of the electron density in different directions creates local electrical fields. An attraction arises from the fields between molecules: namely compression bonding. Solid helium should be formed by molecules held together by this type of bonding.

Figure 1B shows the smallest chain of two molecules held together by this bond. At low temperatures, the London dispersion disappears between helium molecules, resulting in superfluidity because of no attraction between molecules. Solid helium cannot be obtained by simply cooling it further.<sup>[16]</sup> Pressure must be applied to obtain solid helium.<sup>[17]</sup> The formation of compression bonds holds helium molecules together.<sup>[16]</sup> Under pressures of around 400 GPa, hydrogen becomes metallic.<sup>[18-19]</sup> The normal covalent bonds between hydrogen atoms give way to compression bonds, converting the hydrogen from diatomic to metallic.

Because almost everything is subjected to certain pressures on the Earth, compression bonds are common in the absence of other types of bonds, especially for substances composed of a single element. In certain sense, the metallic bond is a result of compression bonding because the way of electron distribution in metal crystals is influenced by adjacent molecules in the compacted space.

The uneven distribution of electron clouds is particularly important in conductors because it enables electrical currents, which is discussed next. If electron clouds are evenly distributed like in isolated atoms, molecules would be pushed apart at large distances, and electrons will be

trapped in atoms of individual molecules preventing them from moving between molecules to form currents.

# **Electrical Current and Resistance**

Without additional energy, an electron's activity is confined in its atomic orbital within a molecule and cannot move between molecules as illustrated in Figure 2A. Between molecules is not just an empty space, but a potential barrier. The **border** between molecules is where an electron feels zero Coulombic force, a balance of attractions and repulsions in the fields created by nearby charges. For an electron to move from one molecule to the next, it has to overcome the potential/energy barrier. Thus, there is no current in conductors normally. In a conductor, the distance and potential barrier between adjacent molecules are relatively small due to compression bonding. An electron may be pushed to the border by an electrical field, such as the voltage applied at the two ends of a conductor. An electron may also be lifted as the conductor moves in a magnetic field, which is the technology employed by electrical generators.

Along the border, the lifted electron may drift from one atom to the next atom in a different molecule in the conductor. This process is called **electrodrift**. It is different from electron movement in chemical bonds where electrons move between atoms in the same molecules. An electron (or orbital) hole is created after an electron drifted to the next molecule. The hole is unstable and may be filled soon by an electron from another molecule in a different electrodrift. A series of such drifts results in a current similar to the flow of a cation. After its orbital hole is taken by the other electron, the lifted electron becomes an orphan or free electron. It may continue to drift along the borders between molecules, creating another current. In the conductor, these two flows are usually in opposite directions under the applied electrical field.

During an electrodrift, the energy level of the electron does not change. Therefore, as part of the process to create a current, the electrodrift does not introduce electrical resistance. To lift an electron from the valence orbital to the border requires some work. This energy will not be lost until the electron drop into an orbital hole. At this point, the stored lifting energy is released as radiation or heat, which is the cause of electrical resistance.

As a reminder, in the proposed theory, the cause of electrical resistance is not due to the collision between particles in conductors. In an electrodrift, the electron does not flow randomly but meaders along the borders between molecules at the same energy contour.



Figure 2, Different approaches to enable electrodrift. As illustrated in the figure, each nucleus of atoms creates an electrical field attracting the electrons around. The energy level is represented by the blue curves in the lower portion of the figure. The horizontal direction shows the distance between the atoms. The energy level is represented in the vertical direction. The blue curves indicate the energy level as a function of the distance away from the center of each atom. (A) At a considerable distance, there is an energy barrier between the atoms, separating electrons. To enable electrodrift, electrons must be lifted to the border with energy. (B) The distance between the atoms may be reduced by decreasing temperature or increasing confining pressure. To a certain extent, the valence orbitals are close to the border and an electron at the valence orbitals may drift from one atom to the next without lifting, as illustrated by the red path A-B.

#### Unification of Conductivity and Superconductivity

The distance between molecules may be reduced by decreasing temperature or increasing confining pressure. As the distance is reduced, so is the potential barrier. When a valence electron is at the border, electrodrift may occur naturally without the need for lifting energy, Figure 1B. This is the state of superconductivity. It appears that superconductivity requires no energy at all, which is not true. The energy budget for creating electrodrifts is discussed next.

At a temperature above 0 K, the valence electrons in a conductor are usually maintained at an equilibrium above ground orbitals. Because the net exchange of energy between electrons and their environment is zero, the temperature of the conductor should remain constant. From the perspective of the electron, the total energy  $E_t$  needed to lift the electron from the ground orbital to the border can be decomposed into two components:  $E_v$  the lifting energy from the ground orbital to the valence orbital, and  $E_b$  the lifting energy from the valence orbital to the border,

 $(1) \qquad E_t = E_v + E_b.$ 

 $E_v$  is maintained and supplied by the surrounding environment in the equilibrium.  $E_b$  is the only additional energy needed to raise electrons for electrodrift, which is the work required to create

currents in conductors. When valence orbitals are at the same level as borders, such as in superconductors, the lifting energy is unnecessary for electrodrift, or  $E_b = 0$ . Equation (1) can be simplified for superconductors as

$$(2) \qquad E_t = E_v$$

which indicates the lifting energy for electrons in superconductors is constantly supplied by the environment. At equilibrium, the energy exchange between a superconductor and its environment is at the same rate. From the environment's perspective, its energy loss is compensated by the energy radiated from the superconductors. The entire system is still energy conservative. Theoretically, at 0 K, there is no energy exchange between a superconductor and the environment. The valence orbitals are at the ground level. The equations (1) and (2) still hold because

(3) 
$$E_t = E_v = E_b = 0.$$

Because there is no electron activity at 0 K, superconductivity should not be active either. To understand this point. Let's introduce a new term **superconductivity strength**, which is equivalent to the critical magnetic field of the superconductor. The large the critical field, the stronger superconductivity. It is observed that most conventional low-temperature superconductors are weak, which is due to the weak electron activity at low temperatures. This will be revisited later when we discuss critical fields.

In the proposed theory, the only requirement for superconductivity is that molecules are at a small distance such that the valence orbitals overlap the borders. When the superconductivity condition is met, electrodrifts may pop up anywhere in a superconductor, creating random currents. In other words, random currents are native activities in superconductors.

Notice in this theory, the superconductivity at high temperatures is not different from traditional superconductivity. As long as the distance between molecules can be small enough, valence electrons will be able to drift along the borders. At high temperatures, this is usually achieved with high pressures. The theory further predicts that resistivity in a conductor will reduce with increasing pressure. Thus, both low and high-temperature superconductivity and normal conductivity are unified in a single theory.

# Estimating Lifting Energy

In the next few sections, we will attempt to create a model base on the concepts in the proposed theory to establish a quantitative relationship between resistivity and distance between molecules in conductors. The model is simplified initially and becomes sophisticated by

introducing parameters to account for the electrical fields between molecules due to the compression bonding. The first step is to estimate the required lifting energy.

In conductors, energy  $E_b$  is required to work against electrical fields to lift electrons from valence orbitals to the borders for electrodrift. This is part of the energy that relates to electrical resistivity. To model the resistivity of conductors, we need to estimate the  $E_b$ , which is the work against Coulombic force:

$$(4) F = \frac{Kq_1q_2}{r^2}$$

where *K* is Coulomb's constant, and positive *F* is the repulsive force between signed charges  $q_1$  and  $q_2$  at a distance *r*. To increase the potential  $E_u$  of an electron in the above field, work has to be done to move the electron against the force *F*, which can be computed with

$$(5) \qquad E_u = -\int_{r_1}^{r_2} F dr$$

where  $r_1$  and  $r_2$  are the distances between the centers of the charges before and after the move. The potential energy  $E_u$  for lifting an electron from orbital  $r_1$  to  $r_2$  can be calculated by integrating equation (5) over the force provided in Coulomb's law (4):

(6) 
$$E_u = Kq_1q_2\left[\frac{1}{r_2} - \frac{1}{r_1}\right].$$

Electrons are orbiting around their nuclei. Kinetic energy difference must also be taken into the consideration. When an electron is circulating at a distance r from its nucleus, its centripetal force is

$$(7) F = ma = m \frac{v^2}{r}$$

where *m* is the mass of the electron, *v* is the velocity, *a* is the acceleration, and *F* is provided by Coulombic force given in equation (4). Note, the positive value in equation (4) is a repulsion force. So,

(8) 
$$-\frac{Kq_1q_2}{r^2} = m\frac{v^2}{r}.$$

The kinetic energy  $E_r$  of the electron is

(9) 
$$E_r = \frac{1}{2}mv^2 = -\frac{Kq_1q_2}{2r}.$$

The kinetic energy difference between two orbital  $r_1$  and  $r_2$  is

(10) 
$$E_k = -\frac{Kq_1q_2}{2} \left[ \frac{1}{r_2} - \frac{1}{r_1} \right].$$

The total lifting energy for the electrons from orbital  $r_1$  to  $r_2$  will be

(11) 
$$E_b = E_k + E_u = \frac{Kq_1q_2}{2} \left[ \frac{1}{r_2} - \frac{1}{r_1} \right].$$

Note, between an electron and its nucleus,  $q_1$  and  $q_2$  have different charges. So,  $E_b$  has a positive value. Replacing the charges *e* and *Q* for the electron and nucleus respectively, the equation becomes

(12) 
$$E_b = \frac{KQe}{2} \left[ \frac{1}{r_2} - \frac{1}{r_1} \right].$$

The electron's energy at infinite from the nucleus is zero, e.g.  $r_2 = \infty$ . So, the lifting energy from orbital *r* to infinite is a positive value:

$$(13) \quad E_b = -\frac{KQe}{2r}.$$

So far, we were only considering the lifting energy for an electron in an isolated atom. In a conductor, the effects of adjacent molecules have to be taken into account. To do that, let's start with a simplified model illustrated in Figure 3 with an electron between two equivalent nuclei. The orbitals at different energy levels are indicated by the contours. The blue line  $R_v$  represents the radius of the valence orbital of the electron. The radius of the borders is indicated by the red stroke  $R_b$ . The **conduction distance** is the distance between the border and valence orbital in an atom denoted by the symbol  $D_c$  (=  $R_b - R_v$ ).



Figure 3, A simplified model for parameters between resistivity and intermolecular distance, illustrated with an electron between two nuclei. The contours represent the orbitals at different energy levels intersecting with a plane through the centers of the nuclei. The short stroke indicates the radius of valence orbitals in blue and the radius of borders is in red.

Consider a valence electron on the center line between the two nuclei. The Coulombic force that the two nuclei exert on the electron is

(14) 
$$F = KQe\left[\frac{1}{R_v^2} - \frac{1}{\left(2R_b - R_v\right)^2}\right]$$

where e is the charge of the electron and Q is the equivalent charge of each nucleus. Let's also include the attractions of two nuclei along the center line on both sides of the two nuclei. Equation (14) needs to be adjusted:

(15) 
$$F = KQe\left[\frac{1}{R_v^2} - \frac{1}{(2R_b - R_v)^2} + \frac{1}{(2R_b + R_v)^2} - \frac{1}{(4R_b - R_v)^2}\right].$$

Again, let's include the attractions from two nuclei further down the line, so on and so forth:

(16) 
$$F = KQe \sum_{i=0}^{\infty} \left[ \frac{1}{\left(2iR_b + R_v\right)^2} - \frac{1}{\left(2(i+1)R_b - R_v\right)^2} \right].$$

In conductor crystal, there will be also molecules on either side of the center line. Considering a sizable conductor, it is reasonable to assume there is an infinite number of molecules on both sides of the center line. Because of the symmetry, the attractions of these molecules are canceled. In fact, except for the molecules along the center line, the attractions of all the other

molecules in the conductor are canceled. For an electron on the center line, we only need to consider the molecules along the line. Therefore, equation (16) is sufficient.

The model is initially constructed with nuclei without surrounding electrons. To be more realistic, the model can be modified by increasing the nuclei size with a corresponding number of electrons around them. With the additional electrons, the term Q may be interpreted as equivalent positive charges that exert the electrostatic force at the valence electron so that the model still holds.

The potential energy difference  $E_u$  or the energy needed to move the electron along the center line from the valence orbital to the border can be computed by integrating equation (5) over the force provided in equation (16) from  $R_v$  to  $R_b$ :

(17) 
$$E_u = -\int_{R_v}^{R_b} KQe \sum_{i=0}^{\infty} \left[ \frac{1}{\left(2iR_b + r\right)^2} - \frac{1}{\left(2(i+1)R_b - r\right)^2} \right] dr.$$

Integration can be applied to each term in the summation:

(18) 
$$E_u = - KQe \sum_{i=0}^{\infty} \left[ \frac{-1}{2iR_b + r} + \frac{-1}{2(i+1)R_b - r} \right]_{R_v}^{R_b}.$$

With the conduction distance  $D_c$ 

$$(19) \quad D_c = R_b - R_v$$

the result can be simplified:

(20) 
$$E_u = - KQe \sum_{i=0}^{\infty} \frac{2D_c^2}{(2i+1)R_b \left( \left( (2i+1)R_b \right)^2 - D_c^2 \right)}$$

where both *e* (-1.60217663×10<sup>-19</sup> *C*) and *K* (8.9875517923×10<sup>9</sup>  $kgm^3s^{-2}C^{-2}$ ) are constants. To simplify the equation, let's introduce a new constant

(21)  $Z = -Ke = 1.43996454425 \times 10^{-9} kgm^3 s^{-2} C^{-1}$ .

Equation (20) can be simplified with the new constant *Z*:

(22) 
$$E_u = ZQ \sum_{i=0}^{\infty} \frac{2D_c^2}{(2i+1)R_b \left( \left( (2i+1)R_b \right)^2 - D_c^2 \right)}.$$

To estimate kinetic energy for an electron at a distance r from the nucleus, let's apply the same logic in equations (7), (8), and (9) with the consideration of all the molecules along the center line:

(23) 
$$E_r = -\frac{1}{2} KQe \sum_{i=0}^{\infty} \left[ \frac{r}{(2iR_b + r)^2} - \frac{r}{(2(i+1)R_b - r)^2} \right]$$

The kinetic energy difference between border  $R_b$  and valence orbital  $R_v$  is

(24) 
$$E_k = \frac{1}{2} K Q e \sum_{i=0}^{\infty} \left[ \frac{R_v}{\left(2iR_b + R_v\right)^2} - \frac{R_v}{\left(2(i+1)R_b - R_v\right)^2} \right]$$

With  $D_c$  from equation (19) and constant Z from equation (21), the above equation can be simplified:

(25) 
$$E_k = ZQ \sum_{i=0}^{\infty} \frac{-2(2i+1)D_c R_v R_b}{\left(\left((2i+1)R_b\right)^2 - D_c^2\right)^2}$$

The total lifting energy is the sum of the potential energy and kinetic energy estimated in equations (22) and (25), respectively:

(26) 
$$E_b = E_u + E_k$$
  
=  $ZQ \sum_{i=0}^{\infty} \frac{2D_c \left[B^2 (2D_c - R_b) - D_c^3\right]}{B \left[B^2 - D_c^2\right]^2}$ , where  $B = (2i + 1)R_b$ .

We will show that the summation term in this equation is proportional to the electrical resistivity of the conductor. Let's name it the **resistive distance**:

(27) 
$$D = \sum_{i=0}^{\infty} \frac{2D_c \left[B^2 \left(2D_c - R_b\right) - D_c^3\right]}{B \left[B^2 - D_c^2\right]^2}$$
, where  $B = (2i + 1)R_b$ .

Equation (26) estimates the energy needed to lift an electron from the valence orbital  $R_v$  to the border  $R_b$  along the center line between the two atoms. The model predicts the lifting energy is zero when  $D_c = 0$ . The condition  $D_c = 0$  means the valence electron at the border or the valence orbital overlapping the border. This is the condition for superconductivity.

#### **Electrical Resistivity and Resistive Distance**

Electrical resistivity is a fundamental property of a material that measures how strong it resists electric current. In this section, we will find its macroscopic representation: the resistive distance, which can be expressed as a function of the conduction distance and valence orbital radius of a conductor. Equation (26) provides a connection between the lifting energy and microscopic properties of conductors, which reveals the fundamentals of resistivity at the microscopic level. The equation estimates the energy needed to raise a single electron from the valence orbitals to the border. To provide equivalent lifting energy, the applied voltage v to a single electron e would be

$$(28) \quad v = \frac{E_b}{e}.$$

Assume a voltage *V* is applied to the ends of a conductor with a cross-section area a (1  $m^2$ ) and *I* meters long. The voltage lifts and drives *n* electrons through the conductor in *t* seconds. Hence, the total voltage *V* should be the sum of the lifting voltage for each electron:

$$(29) \quad V = nv = \frac{nE_b}{e}.$$

By definition, the current *I* created by *V* is

$$(30) \quad I = \frac{en}{t}.$$

The relationship between the electrical resistance R of a conductor, the voltage V applied to the conductor, and the current I created in the conductor is described in Ohm's law:

$$(31) \qquad R = \frac{V}{I} = \frac{tE_b}{e^2}.$$

Applying the definition of resistivity and *R* provided in equations (31), resistivity  $\rho$  can be expressed in terms of *e*, *t*, *a*, *l*, and  $E_{L}$ :

(32) 
$$\rho = R \frac{a}{l} = \frac{atE_b}{le^2}.$$

Replacing  $E_{h}$  provided in equation (26), the electrical resistivity becomes

$$(33) \quad \rho = \frac{atZQ}{le^2}D$$

where *a* (1  $m^2$ ) is the cross-section area of the conductor specimen, both *e* (-1.60217663×10<sup>-19</sup> *C*) and *Z* (1.43996454425x10<sup>-9</sup> kgm<sup>3</sup>s<sup>-2</sup>C<sup>-1</sup>) are constants. Let's introduce a new constant

(34) 
$$L = \frac{aZ}{e^2} = 5.6095886208 \times 10^{28} kgm^5 s^{-2} C^{-3}.$$

Now, equation (33) can be simplified:

$$(35) \quad \rho = \frac{t}{l} L Q D,$$

where t is the time that electrons take to move through the conductor of length *I*. They measure the drifting velocity of the electrons *v*:

$$(36) \quad v = \frac{l}{t}.$$

Therefore, the equation (35) for resistivity can be further simplified:

(37) 
$$\rho = \frac{LQ}{v}D.$$

This equation reveals the correlation between the electrical resistivity and resistive distance D of a conductor. Electrical resistivity is proportional to the resistive distance, which is a function of the distance between molecules at the microscopic level. Thus, all the properties and phenomena related to resistivity and superconductivity can be addressed from the microscopic level with resistive distance. This is the base of the proposed theory.

#### Improved Model for Resistive Distance

Before applying the model for some predictions, let's improve it with the understanding of electron distribution in the compacted environment discussed early. Compression bonding is a result of the uneven distribution of electron clouds between molecules in conductors. In the previous model, the two nuclei are treated as the same equivalent charges. Because of the uneven electron distribution, the two nuclei should be treated differently. By introducing a factor for the coefficiency, we can simulate the uneven fields that the electron is felt from the two molecules, which are the combined fields of the nuclei and their electrons as a whole. Before doing so, let's further investigate the convergence of the summation series in equation (27):

(38) 
$$D = \sum_{i=0}^{\infty} \frac{2D_c \left[ B^2 \left( 2D_c - R_b \right) - D_c^3 \right]}{B \left[ B^2 - D_c^2 \right]^2}$$
, where  $B = (2i + 1)R_b$ .

Fortunately, *D* converges very fast. Numerical simulation shows that its value is bounded in a small range:

$$(39) \quad 1 < \frac{D}{d} < b$$

where *d* is the first term of the series:

(40) 
$$d = \frac{2D_c \left(R_b^2 \left(2D_c - R_b\right) - D_c^3\right)}{R_b \left(R_b^2 - D_c^2\right)^2}$$

The upper bound *b* is a little smaller than 1.0518. This upper bound is for very small  $D_c$ , meaning the distance between molecules is very small. The upper bound *b* decreases towards 1 as  $D_c$  increases towards  $R_b$ . So, the first turn *d* is very close to the entire series *D* for the resistive distance in general. Thus, *d* is sufficient for qualitative analysis.

Now, let's improve the model by introducing an adjustment coefficient c for the force due to the next molecule. Different values c may be used to simulate the field asymmetry between the two models at different levels. With the coefficient c, the Coulombic force exerted on the electron by both molecules can be adjusted based on equation (14):

(41) 
$$F = KQe\left[\frac{1}{r^2} - \frac{c}{\left(2R_b - r\right)^2}\right]$$

where r is the distance of the electron from the center of the molecule and *c* is the adjustment coefficient for the next molecule,  $c \le 1$ . When c = 1, it models the two molecules that have equivalent fields, therefore resulting in the same model as equation (40). With c = 0, it simulates the single molecule model and the result will be the same as equation (12). When c < 0, it models the strong repulsion effect due to the electrons in the next molecule. The potential energy difference between orbital at distance  $R_v$  and  $R_b$  is

(42) 
$$E_u = -\int_{R_v}^{R_b} KQe \left[\frac{1}{r^2} - \frac{c}{(2R_b - r)^2}\right] dr.$$

The result of integration is

(43) 
$$E_u = ZQ \left[ \frac{-1}{r} + \frac{-c}{2R_b - r} \right]_{R_v}^{R_b}$$

or

(44) 
$$E_u = ZQ \left[ \frac{1}{R_v} + \frac{c}{2R_b - R_v} - \frac{1}{R_b} - \frac{c}{R_b} \right]$$

Similarly, the kinetic energy of the electron in an orbital at a distance r from the center of the molecule can be found with:

(45) 
$$E_r = -\frac{1}{2} KQe \left[ \frac{1}{r} - \frac{rc}{(2R_b - r)^2} \right]$$

The kinetic energy difference between orbital  $R_b$  and  $R_v$  is

(46) 
$$E_k = E_{R_b} - E_{R_v} = \frac{1}{2} Z Q \left[ \frac{1}{R_b} - \frac{c}{R_b} - \frac{1}{R_v} + \frac{R_v c}{\left(2R_b - R_v\right)^2} \right].$$

The first term estimate for total lifting energy  $E'_{b}$  is the sum of the potential energy and kineitic energy:

(47) 
$$E_{b}^{'} = E_{u} + E_{k} = ZQ \left[ \frac{1}{2R_{v}} - \frac{1+3c}{2R_{b}} + \frac{c(4R_{b}-R_{v})}{2(2R_{b}-R_{v})^{2}} \right]$$

or in terms of  $R_b$  and  $D_c$ 

(48) 
$$E_{b}^{'} = \frac{ZQ}{2} \left[ \frac{1}{R_{b} - D_{c}} - \frac{1 + 3c}{R_{b}} + \frac{c(3R_{b} + D_{c})}{(R_{b} + D_{c})^{2}} \right]$$

or simplified to

$$(49) \qquad E_{b}^{'} = \frac{ZQ}{2}d$$

where *d* is the resistive distance with the adjustment of coefficient *c* for the next molecule:

(50) 
$$d = \frac{(5c-1)\left(R_b D_c^2 - R_b^2 D_c\right) + (1+3c)D_c^3}{2R_b \left(R_b - D_c\right) \left(R_b + D_c\right)^2}.$$

This is the same as equation (40) when c = 1. The first term estimate for electrical resistivity  $\rho'$  is

(51) 
$$\rho' = \frac{LQ}{v}d.$$

With  $R_v$  (=  $R_b$  -  $D_c$ ), equation (50) can be refactored as

(52) 
$$d = \frac{N}{2R_{v} \left(\frac{R_{v}}{D_{c}} + 1\right) \left(\frac{R_{v}}{D_{c}} + 2\right)^{2}} \text{ where } N = (3c + 1) - (5c - 1) \frac{R_{v}}{D_{c}} \left(\frac{R_{v}}{D_{c}} + 1\right).$$

Equations (51) and (52) provide a connection between electrical resistivity and microscopic properties of conductors, such as conduction distance  $D_c$ , valence orbital radius  $R_v$  and adjustment coefficient *c*. Adjustment coefficient *c* is a property related to molecule structure and specific to each kind of conductor. With property *c*, we should be able to compute the electrical resistivity for a conductor from its conduction distance and valence orbital radius. The model should be validated if there is accurate data.

Without accurate data, nevertheless, the model can still be justified by some rough numbers. Let's take c = 0.1, border, and valence orbital radii from ptable. The results do show the correspondence between electrical resistivity (column Resistivity) and resistive distance (column Resistive *D*), Table 1. The non-conductive materials silicon and diamond stand out from the metals.

Name	Symbol	Border Ra	Valence Ra	Resistive D (1/m)	Resistivity (m/MS)
Silicon	Si	210	111	5.37E+13	1.00E+03
Diamond	С	170	77	8.50E+11	1.00E+01
Aluminum	AI	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, Resistive distance  $(m^{-1})$  in column Resistive D calculated using equation (52). Other data are from <u>ptable site</u>. Column Border Ra is used for the border orbital radius taken from the Van de Waals radius or empirical radius for Ca, Fe, and Al. Column Valence Ra is used as the valence orbital radius taken from the covalent radius.

# **Conducting Orbital and Conducting Zone**

Now, we can predict the superconductivity condition with different adjustment coefficients *c* using the model. The condition for superconductivity is resistivity  $\rho = 0$ . From equations (51) and (52), this condition is equivalent to N = 0:

(53) 
$$(3c + 1) - (5c - 1)\frac{R_v}{D_c} \left(\frac{R_v}{D_c} + 1\right) = 0.$$

Solve the equation to find a solution for  $R_v/D_c$  ratio:

(54) 
$$\frac{R_v}{D_c} = \sqrt{\frac{17c+3}{4(5c-1)}} - \frac{1}{2}.$$

With c = 0, there is no real solution to the equation. We only care about the solution for  $R_v/D_c$  in the real domain even though there are imaginary solutions to the equation. The physical interpretation in this situation is that, if a valence electron cannot feel any Coulombic force from adjacent molecules, it is unable to transition to a superconductivity state without additional lifting energy. More specifically, there is no real solution to the equation if c is  $\frac{1}{6}$  or smaller. That is superconductivity will not occur if the adjacent molecule cannot provide sufficient Coulombic force. It does not mean that superconductivity is not possible because the adjustment coefficient c may increase with pressure.

With c = 1, a valence electron feels an equivalent Coulombic force from an adjacent molecule as from its parent molecule at the same distance. This may be the situation when there is an orbital hole in the adjacent molecule, after an electrodrift. The solution for the superconductivity condition is  $D_c = 1.618R_v$ . It means that if a valence electron is next to a molecule with an orbital hole, it can drift to the next molecule without lifting energy whenever the conduction distance is within 1.618 times its orbital radius.

The adjustment coefficient *c* is normally between 0 and 1, adjusted in the compression bonding. For instance,  $c = \frac{1}{4}$ , the superconductivity condition will be  $D_c = 0.456R_v$ . Because the adjacent molecule exerts less Coulombic force on the valence electron, to become superconductive, molecules must be next to each other at a much closer distance.

From the solutions above, we can determine that electrodrift or conduction does not have to be on the border, but can occur at even lower orbitals. This is the valence orbital with an  $R_v$  at the solution for the superconductivity solution. Let's give this orbital a special term **conducting orbital** with a radius  $R_c$ . The reason that electrodrift can occur below the border is because of the Coulombic force from the adjacent molecule. Without energy exchange in a single atom, an electron will be stable in its orbital. Even if there are perturbations, the total potential and kinetic energy are conservative. The orbital is the result of an electron perturbating along its orbit. As the electron moves higher, its potential energy increases, reducing its kinetic energy. The decrease in kinetic energy causes the electron to move slower and fall back to the lower level, decreasing its potential energy while increasing its kinetic energy. Thus, the electron is perturbating around its equilibrium orbit in an overall stable orbital. However, with the Coulombic force from an adjacent molecule, this stable will be broken at the conducting orbital. Beyond the conducting orbital, the Coulombic force from the adjacent molecule will pull the electron off its stable orbital, resulting in an electrodrift. The **conducting zone** is defined as the region between conducting orbitals of adjacent molecules. The difference between normal conductors and superconductors is that the valence orbitals of conductors are below the conducting zone while the valence orbitals of superconductors are in the conducting zone. Thus, electrodrifts in superconductors occur without lifting energy while electrons in conductors must be lifted to the conducting zone. Now, the difference between insulators, conductors, and superconductors can be quantitatively based on the solution to equation (53). For a material with an adjustment coefficient *c*, if there is no real solution to the equation, the material is an insulator. If there are real solutions, the material is either a conductor or a superconductor, depending on its valence orbital  $R_v < R_c$  or  $R_v >= R_c$ .

### **Orbital Dynamics**

The dynamic aspect of electron orbitals has not been touched on in the discussion so far. Valence orbitals, conducting orbitals, conducting zones, conduction distances and adjustment coefficients change with temperature and pressure, especially pressure. Some of the aspects are the subjects next.

First, let's investigate the impact of pressure changes. When increasing the pressure to a conductor while maintaining all other parameters the same, the space between molecules is squeezed, resulting in decreasing  $D_c$  and increasing  $R_v/D_c$ . For a conductor with c >= ½, the resistivity  $\rho$  decreases because *d* decrease according to equation (54). This explains why resistivity decreases with increasing pressure.

With sufficient pressures,  $D_c$  can be small enough such that  $R_v \ge R_c$ , which is the condition for superconductivity. This is because, with a specific coefficient *c*, the superconductivity condition from the solution to equation (53)

(55) 
$$\frac{R_c}{D_c} = \sqrt{\frac{17c+3}{4(5c-1)}} - \frac{1}{2}$$

is a fixed value.  $R_c$  decreases with  $D_c$ . In other words, pressure not only reduces the conduction distances but also pushes conducting orbitals down such that valence orbitals can be in the conducting zones. This is the reason many superconductors are obtained at high pressures.

More interestingly, under pressure, some expected insulators become superconductors. Adjustment coefficients increase with pressure, which turns insulators into superconductors. As mentioned earlier, insulators do not have real solutions to equation (53). Solutions will be found in the real domain when *c* is large enough. The electron cloud distribution between molecules can be changed under pressure, resulting in compression bonding. The adjustment coefficient c is closely related to the formation of the compression bonding as it will change the field structure between molecules.

## **Superconducting Phase**

Conventional superconductors are usually obtained at low temperatures. Temperature decrease has several effects. Valence orbitals retreat to low orbitals, reducing the size of molecules and weakening the intermolecular repulsions. Less frequent electron exciting at low temperatures further curtails the repulsions. Both effects reduce the distance between molecules and  $D_c$ . Most of the conventional superconductors are obtained at normal pressures on the Earth. It is effectively increasing the pressure as temperature reduces because molecules are less repulsive at low temperatures. As a result,  $R_c$  decreases faster than  $R_v$ , which puts valence orbitals into the conducting zone.

Reducing temperature has a similar effect as increasing pressure, which reduces the resistivity of conductors, and vice versa. Superconductivity is only obtained in certain materials at low temperatures. If the pressure is increased actively, superconductivity should be obtained for all the materials with sufficient pressures. In general, the resistivity of any matter correlates to the distance between molecules, which is a function of temperature and pressure. The resistivity of a conductor decreases with temperature or increasing pressure, and vice versa. The critical temperature of a superconductor also increases with pressure. An insulator may become conductive, or even superconductive under sufficient pressure. This explains that some ceramics, expected insulators, were discovered recently to be superconductors at high pressures.

Just like solids, liquids, and gases are different mechanical shear-resisting phases, there should also exist different **electrical resisting phases**: insulating phase, conducting phase, and superconducting phase. The critical point of a conventional superconductor is just the transition temperature observed at the normal pressure on the Earth. Numerous critical points may be observable at different pressures for the same superconductor. All the combinations of different critical temperatures and pressures should draw a superconducting phase transition boundary on a state diagram, as illustrated in Figure 4.



Figure 4, An illustrative state diagram with a superconducting phase boundary. According to the proposed model, superconductivity phase transitions occur at different combinations of temperatures and pressures. Connecting all the combination points forms a superconducting phase transition boundary as illustrated by the blue curve. Similar to ordinary mechanical shear-resisting phases of matter, superconductivity is an electrical-resisting phase of matter, to the low-temperature side of the superconducting phase transition boundary. The critical point of a conventional superconductor is just the transition temperature on the curve at the normal pressure on the Earth.

Equation (51) can be interpreted as a 3-D surface of resistivity over a pressure-temperature domain. The phase transition boundary is the intersection between the surface and the plane at resistivity  $\rho = 0$ . The solution (55) describes the boundary curve. Each point on the boundary is a critical point of temperature at that pressure. At that pressure and temperature, the valence orbital is right on the conducting orbital,  $R_v = R_c$ .

The blue curve illustrates a phase transition boundary between normal conductors and superconductors. The actual phase transition boundary for some materials may not be a smooth curve due to the discrete nature of atomic orbital structures. Some superconducting phase transition boundaries may be stepwise for materials with large energy gaps between different orbital levels.

If superconductivity is an ordinary state of matter as predicted in the proposed theory, why superconductors are not as common as conductors? It is because the normal combinations of temperatures and pressures on the Earth are not favorable for superconductivity. Figure 5A shows superconductivity observed at low temperatures.



Figure 5, The significant difference between superconductors and non-superconductors is the molecular distance. (A) A conventional superconductor is usually observed at low temperatures where the valence orbitals are so close to each other and in the drifting zone. Electrodrift occurs freely without the need to lift electrons. (B) As temperature increases, atoms are pushed apart due to the increasing intermolecular repulsion as a result of electrons excited to higher orbitals. The borders expanse faster than the valence orbitals. The separation of the valence orbitals disables free electrodrift, which destructs the superconductivity.

As temperature increases, electrons excite to higher orbitals. Valence orbitals expand to high energy levels. The molecule size increases, and so does  $R_v$ . Intermolecular repulsion increases. Molecules are pushed apart, and so increases  $D_c$  and  $R_c$ , Figure 5B. Lacking confining pressure on the Earth,  $R_c$  increases faster than  $R_v$  due to the increasing repulsion, which puts valence orbitals out of the conducting zone. This is why conventional superconductivity is destructed at room or high temperatures.

#### **Meissner Effect**

A superconductor is not only a perfect conductor but is more significant because of the Meissner effect, a phenomenon where an external magnetic field is expulsed from the superconductor during the transition to the superconducting phase.<sup>[9]</sup> Note, that a magnetic field created by induction requires a change in magnetic flux according to Faraday's law of induction.<sup>[20-21]</sup> The Meissner effect is observed during the transition to the superconducting

phase in an existing magnetic field where there is no change in magnetic flux. In other words, the Meissner effect is not because of induction. Rather, it is caused by currents that arise after the superconducting phase transition. Electrodrift in superconductors results in spontaneous random currents. Normally, the currents would not create observable external magnetic fields because the randomly created fields cancel each other locally. When there is an external magnetic field, the directions of electron flows will be deflected by the Lorentz force given by

$$(56) \quad F = q(E + v \times B)$$

where q is the electrical charge, v is the velocity of the charge, B is the magnetic field, E is the electric field (not applicable in this context), and F is the force exerted on the charge.<sup>[22-24]</sup> Looking in the direction of the applied magnetic field, a moving electron is deflected by the Lorentz force to circulate in a clockwise direction. Deflected by the Lorentz force, any flow of charges in a superconductor reorients in circular directions creating a magnetic field that compensates the applied magnetic field inside of the superconductor and superimposes the applied field outside of the superconductor. The net result appears as if the applied field is expelled from the superconductor.

On the other hand, BCS theory cannot account for the Meissner effect. Even if there might exist Cooper pairs of electrons in superconductors, there is no mechanism to drive the electron pairs. Motionless Cooper pairs cannot be deflected by an applied magnetic field because F = 0 when v = 0 and E = 0.

# **Critical Current Density**

The critical current is the maximum current density that a superconductor can sustain. The critical current of a superconductor determines the critical magnetic field discussed in the next section.

Based on Stefan-Boltzmann's law, the energy-emitting rate from a blackbody is proportional to the fourth power of its absolute temperature. Thus, the temperature of an object is an indicator of its energy-emitting rate. At equilibrium, the energy emission and absorption of a body are at the same rate. So, the temperature is also a measurement of the energy absorption rate of the body. Every excitement of electrons results from energy absorption. So, the temperature also correlates to the electron exciting rate in the body.<sup>[14]</sup>

In a superconductor, a certain portion of the excited electrons results in an electrodrift. The activity of electrodrifts initiates currents and determines the maximum current density in a superconductor. The higher the temperature, the higher the maximum current density. Hence, it can be predicted that the critical temperature determines the critical current in a superconductor. We will also show in the next section that it is the critical current that determines the critical magnetic field.

As predicted above, the critical temperature of a superconductor increases with pressure increases. So, the critical current in a superconductor also increases as the pressure increases. There should also be a correlation between critical temperatures and critical currents.

## **Critical Magnetic Field**

In an external magnetic field, a superconductor will lose its superconductivity when the applied field increases over a certain strength, known as the critical magnetic field  $B_c$ . At a low strength, an external magnetic field is expulsed from a superconductor by the Meissner effect. As the strength of the external field increases, the internal field will increase accordingly just enough to compensate for the applied field.

However, as discussed earlier, there is a limit to the maximum current density in a superconductor at a given temperature, known as the critical current. Over the critical current, the external field is no longer compensated completely inside a superconductor. The applied external field cannot be expulsed entirely by the Meissner effect. The remaining field diverts the orbital orientations of electrons around each atom in the superconductor.

Figure 6 compares normal electron clouds with electron clouds deformed by an applied magnetic field. In a small or no magnetic field, normal electron clouds extend in all directions evenly, Figure 5A. In a magnetic field greater than a critical level, the orbitals of electrons are deflected by the Lorentz force and reorient their orbital plane perpendicular to the field direction. The orbitals become squashed like lanterns. This effectively flattens the clouds in the direction of the applied field, Figure 5B. When the field is strong enough, the valence orbitals may be separated, therefore destructing the superconductivity. The valence electrons are significant to superconductivity and are affected most due to less tangling effect from other electrons in the same atom.

The failure of superconductivity above the critical field is due to the limit of critical current at the critical temperature. As predicted in the last section, a higher critical temperature corresponds to a larger critical current. Consequently, there should be a similar correlation between critical temperature and critical magnetic field. This prediction has already been verified by the strong correlation observed between critical temperatures and critical magnetic fields in different superconductors.



A, Normal Electron Cloud

B, Deformed in Magnetic Field

Figure 6, An illustration of superconductivity destroyed in a magnetic field. (A) In a small or no magnetic field, the valence orbitals extend evenly in a superconductor, intersect the drifting zone and enable free electrodrift. At a low external magnetic field, the internal field of the superconductor is expulsed due to the Meissner effect. Superconductivity may sustain a magnetic field up to a critical level. (B) At an external field above the critical level, the internal magnetic field cannot be completely compensated due to the limit of critical current. Deflected by the Lorentz force in the remaining field, electrons divert their orbiting plane in the direction perpendicular to the field, which deforms the shape of the electron clouds like squashed lanterns perpendicular to the applied field. As a result, the valence orbitals fall apart. Energy barriers are reestablished between molecules, preventing electrons from electrodrift and destroying the superconductivity.

#### **Critical Field Magnitude**

The critical magnetic field  $B_c$  is tabulated  $B_{co}$  at 0 K and decreases from that magnitude with increasing temperature T, reaching zero at the critical temperature  $T_c$  for superconductivity. The critical magnetic field at any temperature below the critical temperature is given by

(57) 
$$B_c = B_{c0} \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right].$$

The increase in the critical magnetic field relates to an increase in the overlapping area of valence orbitals over the conducting zone as superconductors are cooled over critical temperatures.

Perturbation is one characteristic of electrons due to their small size and easily subject to the impact of photons and fields from adjacent particles. An orbital is a region where the electron appears at a certain probability. In a cross-section of an orbital, an electron appears at the highest probability at the center of the orbital and the probability decreases towards both sides.

Nevertheless, the combination of the potential and kinetic energy of an electron is conservative at a certain orbital. Normally, without additional energy, an electron is confined in a molecule under a valence orbital. However, when the valence orbital is close enough to the conducting orbital, the perturbation may cause the electron to drift along the border to the next molecule. This is not because the electron gains some extra energy, but due to part of the kinetic energy being transferred to potential energy just enough to move into the border. Electrodrift starts occurring with a small probability when the valence orbitals begin to overlap the conducting orbital. The probability increases with more overlapping areas.

The overlap area of the intersection usually increases with decreasing temperature as the distance between molecules decreases with intermolecular repulsion decreases along with the temperature. The critical temperature is the temperature when valence orbitals just intersect the drifting zone. At this point, the valence orbitals can be easily disjoined when distorted under a small external magnetic field. At low temperatures, because there is a wider intersection area between valence orbitals and the drifting zone, it requires a greater magnetic field to distort the electron clouds to completely disjoin the intersection. In addition, a wider intersection area also leads to more currents because a higher percentage of the excited electrons will fall in the area for electrodrift. This explains the negative relationship between temperatures and critical fields given in equation (57).

## **Type-II Superconductor**

A type-II superconductor has two critical fields:  $B_{c1}$  and  $B_{c2}$ .<sup>[25-27]</sup> Normal superconductivity is observable at an applied magnetic field below  $B_{c1}$ . With a field above  $B_{c1}$ , the superconductivity is destructed in certain areas of the superconductor. These non-superconductive islands are called magnetic vortices. The density of the vortex increases with the strength of the applied magnetic field. When the field is over  $B_{c2}$ , the superconductivity is completely destroyed. Type-II superconductors are usually made of alloys or compounds.

Figure 6 illustrates one possible crystal structure made of two different molecules. The ordinary superconductivity is observable at a magnetic field  $B < B_{c1}$ , Figure 7A. This is because the applied field is below all the critical fields. All molecules are in the superconducting phase. The entire superconductivity is destructed at the field  $B > B_{c2}$ , Figure 7C.  $B_{c2}$  is the maximum critical field for all the materials. In a field above  $B_{c2}$ , the superconductivity for every type of material is destroyed. In a field between  $B_{c1}$  and  $B_{c2}$ , Figure 7B, the superconductivity for the central molecule is destroyed while other molecules surrounding it still remain in the superconducting phase. The center part becomes a non-superconductive island, known as the magnetic vortex which allows the magnetic flux to penetrate.

The crystal structure of type-II superconductors usually has different arrangements of atoms/molecules in different directions. Different deflection/flattening effects of electron clouds may be observed in magnetic fields applied in different directions. As a result, the

superconductivity may be destructed at a different field strength in a different direction. This effect is also illustrated in Figure 7. The two critical magnetic fields are observed with an external field applied at a small angle. Different critical fields should be observed with a field applied at a different angle. Because the geometry of the deformed electron clouds changes with the direction of the applied field, the valence orbitals will become disjoined at different field strengths.



Figure 7, The responses of a type-II superconductor made of alloys to magnetic fields. (A) At a magnetic field below the first critical level, the valence orbitals are intersecting, resulting in a normal state of superconductivity. (B) At a magnetic field between the first and second critical level, the electron clouds of molecules are deformed to an extent that small molecules are isolated from others, but large molecules are still intact. The superconductivity for the small molecules is destructed, resulting in vortices or superconducting holes in a mixed state of superconductivity. (C) At a magnetic field greater than the second critical field, the entire superconductivity is destroyed. As the electron clouds deform further in the stronger field, The valence orbitals between large molecules are also separated.

Each critical magnetic field relates to an intersection/disjoin of some valence clouds in superconductors. With type-II superconductors made of alloys or compounds, valence clouds may become intersected and disjoined in various manners. Each type of molecule creates one or more intersection configurations between the same type of molecules and different types of molecules. So, there is at least one critical field for each type of molecule in a type-II superconductor. The number of critical fields is usually more than the types of molecules.

Because the molecule shape of compounds is usually asymmetrical, the intersection between molecules may come with different formations, which are likely disjoined in different manners. This is another cause for there to be more critical magnetic fields for type-II superconductors than molecule types. The two critical fields often discussed in the literature are just the minimum and maximum of all the critical magnetic fields. In the mixed state of a type-II superconductor, vortices are the area of destructed superconductors. The vortex area increases along with

increasing the applied field as different critical fields are overpassed one by one. Vortices are responsible for flux pinning, also known as quantum locking in quantum levitation, which makes type-II superconductors more interesting and valuable for applications.

## Flux Quantization

Magnetic flux is a measurement of the total magnetic field through a given area. A looping current will result in magnetic flux. The minimum value of flux is created by a single electron circulating an area. Therefore, magnetic flux is quantized. The value of flux quantum  $\Phi_0$  can be deducted by applying some gauge transformations to the Schrödinger equation. Knowing that the phase of the ware function depends on the gauge and the physical predictions do not depend on the gauge, we can conclude

$$(58) \quad \Phi_0 = \frac{h}{2e}$$

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

In the proposed theory, currents in a superconductor arise from electrodrift. Each electrodrift creates a temporary anion and a cation simultaneously. The drifting of them results in one flow of a negative charge and another of a positive charge. The minimum flux is created by the two flows in opposite directions around a donut-shaped superconductor, which is equivalent to two electrons moving in the same direction around the donut. Thus, the proposed theory predicts the minimum flux in a superconductor to be twice flux quantum  $\Phi_0$ . This prediction is confirmed in experiments by B. S. Deaver and W. M. Faibank<sup>[28]</sup> and, independently, by R. Doll and M. Näbauer.<sup>[29]</sup>

# Hints for Superconductor Search

Figure 8 highlights all known superconductive elements in blue boxes. They match very well with the elements still in liquid or solid phases at 3500 K, Figure 9. This observation also aligns with the logic of the proposed theory. As shown in equation (52), the criterion for superconductivity is small  $D_c$  compared with  $R_v$ . A small distance between molecules indicates there is less intermolecular repulsion. Electrodrift requires less lifting energy between molecules at small distances. Materials composed of those molecules are better candidates for superconductors. High-repulsive molecules are likely to push the molecules apart and turn them into gas. In this logic, the elements still have not transitioned to gas at 3500 K are less repulsive, have smaller intermolecular distances, and therefore are better candidates for superconductors.

Ceramics are used in rocketry as heat insulators because of their high melting points. In the same logic, they should be less repulsive between molecules, have smaller molecular distances, and be better superconductor candidates. This property explains why these well-known electrical insulating ceramics can be superconductors. This leads to the first hint in searching for superconductors. That is to look for materials with molecule structures that create less repulsion between molecules.

н		Sb         Atomic symbol           Critical point, Tc (K)														He	
Li	Be 0.026	Superconductor										В	С	Ν	0	F	Ne
Na	Mg											Al 1.175	Si	Р	S	CI	Ar
к	Ca	Sc	Ti 0.4	V 54	Cr	Mn	Fe	Со	Ni	Cu	<b>Zn</b> 0.85	<b>Ga</b> 1.10	Ge	As	Se	Br	Kr
Rb	Sr	Y	<b>Zr</b> 6.1	Nb 9.25	Mo 0.912	<b>Tc</b> 7.80	<b>Ru</b> 0.49	<b>Rh</b> 0.0003	Pd	Ag	Cd 0.517	In 3.4	<b>Sn</b> 3.72	Sb	Те	I.	Xe
Cs	Ва		Hf 0.128	Ta 4.47	W 0.0154	<b>Re</b> 1.697	<b>Os</b> 0.66	<b>Ir</b> 0.113	Pt	Au	Hg 4.15	TI 1.70	Pb 7.2	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	FI	Мс	Lv	Ts	Og
			La 4.9	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Тb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th 1.38	<b>Pa</b> 1.4	U 1.8	<b>Np</b> 0.075	Pu	<b>Am</b> 1.1	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Figure 8, Known superconductive elements ( $T_c$  from <u>Peter J. Lee's page</u>).



Figure 9, The states of elements at 3500 K (screenshots from ptable site).

Repulsion between molecules is the primary hurdle to overcome for superconductivity. The repulsion between molecules increases quickly as temperature increases, especially for symmetrical molecules. Without a confining pressure, the expansion of valence orbitals at high temperatures increases the repulsion between molecules, which pushes the molecules apart faster than the expansion of valence orbitals themselves. This problem may be evaded with large compounds. The molecule structure of compounds is usually irregular. Large irregular molecules increase the chances of valence cloud intersections due to the uneven distribution of intermolecular repulsions and attractions. This is consistent with the observation that type-II superconductors usually have greater ranges of critical fields than type-I superconductors. So, the second hint to looking for room-temperature superconductors is to focus on type-II superconductors, especially those made of large compounds. Large molecules are usually less repulsive, which is in line with the first hint as well.

## Conclusions

Electrical currents are the results of electrodrift across the border between different molecules at the same energy level. The distance between molecules determines the difference between conducting orbitals and valence orbitals. To create currents in conductors, energy is required to lift electrons from valence orbitals to the conducting zone along borders. The electrostatic force between the electrons and their nuclei causes electrical resistance. More energy is required to

lift electrons at a large distance from the conducting zone. Thus, resistivity correlates to the distance between molecules in conductors. The distance can be reduced by increasing the pressure and decreasing the temperature, and so does the resistivity. To some extent, the resistivity can be reduced to zero, which is where superconductivity is obtained. Superconductors, conductors, and insulators are classified based on the conductivity characteristics of materials at normal temperatures and pressures on the Earth. There may be different electrical resisting phases of the same matter at different combinations of temperatures and pressures. Superconductivity may be an ordinary phase for any matter. This theory provides a comprehensive explanation for conventional and high-temperature superconductors, the Meissner effect, critical current density, critical magnetic field, critical field magnitude, and flux quantization. It predicts critical currents correlate with critical temperatures for different superconductors and also reveals the primary hurdle to superconductors is to look for materials made of less repulsive molecules. Compounds and alloys of large molecules should be the optimal candidates.

## Acknowledgments

Thanks to Peter J. Lee for providing the <u>critical temperatures</u> for superconductive elements in the periodic table. Credit to ptable.com for the screenshots of the <u>melting</u> <u>points of elements</u> from the web pages. We acknowledge Albert Y. Liu and Thomas S. Zhou for their helpful discussions. This work has been supported by Ling Zhang.

## **Revision History**

- <u>06/02/2019: Uncovering the Mystery of Superconductivity</u>
- 06/16/2019: Unified Theory of Resistivity and Superconductivity
- <u>06/18/2021: Unified Theory of Superconductors and Conductors</u>
- 09/08/2022: Unified Theory of Low and High-Temperature Superconductivity
- <u>09/18/2022: Added Sections for Flux Quantization and Isotope Effect</u>
- <u>10/08/2022: Added Superconductivity Energy. Critical Current, and Overcooling Effect</u>
- <u>10/14/2022: Added Sections for Electrodrift and Superconductivity</u>
- <u>10/18/2022: Introduced Resistivity Model and Resistive Distance</u>
- 01/16/2023: Added Compression Bonding, Conducting Orbital, and Conducting Zone

## References

1. Onnes, H.K. (1911). "*The resistance of pure mercury at helium temperatures*". Commun. Phys. Lab. Univ. Leiden. **12**: 120.

- Van Delft, D. & Peter Kes, P. (2010). <u>"The Discovery of Superconductivity"</u>. Physics Today. 63 (9): 38–43. doi:<u>10.1063/1.3490499</u>.
- Bardeen, J.; et al. (1957). "<u>Theory of Superconductivity</u>". Physical Review. **108**. p. 1175. doi:<u>10.1103/physrev.108.1175</u>.
- Bednorz, J.G. & Müller, K.A. (1986). "Possible high T<sub>c</sub> superconductivity in the Ba-La-Cu-O system". Z. Phys. B. 64 (1): 189–193. doi:<u>10.1007/BF01303701</u>.
- Wu, M.K.; et al. (1987). "Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure". Physical Review Letters. 58 (9): 908–910. doi:<u>10.1103/PhysRevLett.58.908</u>. PMID <u>10035069</u>.
- Drozdov, A; et al. (2015). <u>"Conventional superconductivity at 203 kelvin at high pressures in</u> the sulfur hydride system". Nature. 525 (2–3): 73–76. arXiv:<u>1506.08190</u>.
- 7. Schilling, A.; et al. (1993). "Superconductivity above 130 K in the Hg–Ba–Ca–Cu–O system". Nature. **363** (6424): 56–58. doi:10.1038/363056a0.
- Takahashi, H.; et al. (2008). "Superconductivity at 43 K in an iron-based layered compound LaO<sub>1-x</sub>F<sub>x</sub>FeAs". Nature. **453** (7193): 376–378. doi:<u>10.1038/nature06972</u>. PMID <u>18432191</u>.
- 9. Hirsch, J.E. (2012). "*The origin of the Meissner effect in new and old superconductors*". Physica Scripta. **85** (3): 035704. arXiv:<u>1201.0139</u>. doi:<u>10.1088/0031-8949/85/03/035704</u>.
- Drude, P. (1900). "*Zur Elektronentheorie der Metalle*". Annalen der Physik. **306** (3): 566–613. doi:<u>10.1002/andp.19003060312</u>.
- Machado, A.; et al. (2012). "<u>Defect Structure Versus Superconductivity in MeB2</u> <u>Compounds (Me = Refractory Metals) and One-Dimensional Superconductors</u>", doi:10.5772/48625.
- 12. Vaidya, R.; et al. (2003). "*Effect of pressure on electrical resistance of WSe2 single crystal*". Pramana -- Journal of Physics, Vol. 61, No. 1 pp. 183-186.
- 13. Souza, E., et al. (2006). "*Improvement of metallic joint electrical conductivity using a novel conductive paste produced from recycled residues*". Rev. Esc. Minas Vol. 59, No. 2.
- 14. Liu, J.Z. (2022). "Components and Dynamics of Thermal Systems". Stanford University.
- London, F. (1930), "Zur Theorie und Systematik der Molekularkräfte", Zeitschrift für Physik, 63 (3–4): 245, <u>Bibcode:1930ZPhy...63..245L</u>, <u>doi:10.1007/BF01421741</u>, <u>S2CID 123122363</u>. English translations in H. Hettema, ed. (2000), *Quantum Chemistry, Classic Scientific Papers*, Singapore: World Scientific, <u>ISBN 981-02-2771-X</u>, <u>OCLC 898989103</u>, <u>OL 9194584M</u> which is reviewed in Parr, Robert G. (2001), "Quantum Chemistry: Classic Scientific Papers", *Physics Today*, **54** (6): 63–64, <u>Bibcode:2001PhT...54f..63H, <u>doi:10.1063/1.1387598</u>.
  </u>
- 16. Liu, J.Z. (2021). "*Superfluids are not Fluids*". Stanford University.
- 17. Pinceaux, J. P., Maury, J. P., Besson, J. M., <u>Solidification of helium, at room temperature</u> <u>under high pressure</u>. *Journal de Physique Lettres*. **40** (13), 307–308 (1979). <u>doi:10.1051/jphyslet:019790040013030700</u>.
- Ashcroft, N. W., The hydrogen liquids. *Journal of Physics: Condensed Matter.* **12** (8A), A129–A137 (2000). <u>Bibcode:2000JPCM...12..129A</u>. <u>doi:10.1088/0953-8984/12/8A/314</u>.
- Bonev, S. A., et al, A quantum fluid of metallic hydrogen suggested by first-principles calculations. *Nature*. **431** (7009), 669–672 (2004). <u>arXiv:cond-mat/0410425</u>. <u>Bibcode:2004Natur.431..669B</u>.

- 20. Souza, E., et al. (2006). "*Improvement of metallic joint electrical conductivity using a novel conductive paste produced from recycled residues*". Rev. Esc. Minas Vol. 59, No. 2.
- 21. Faraday, M. & Day, P. (1999). "The philosopher's tree: a selection of Michael Faraday's writings". CRC Press. p. 71.
- 22. Huray, P.G. (2010). "Maxwell's Equations". Wiley-IEEE. p. 22.
- 23. Lorentz, H.A. (1895). "Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern".
- 24. Chow, T.L. (2006). "*Electromagnetic theory*". Sudbury MA: Jones and Bartlett. p. 395.
- 25. Hove, J.; et al. (2002). <u>"Vortex interactions and thermally induced crossover from type-I to</u> <u>type-II superconductivity"</u>. Physical Review B. **66** (6): 064524. arXiv:<u>cond-mat/0202215</u>.
- 26. Callaway, D.J.E. (1990). "On the remarkable structure of the superconducting intermediate state". Nuclear Physics B. 344 (3): 627–645. doi:10.1016/0550-3213(90)90672-Z.
- 27. Abrikosov, A.A. (2003). "type II Superconductors and the Vortex Lattice". Nobel Lecture.
- 28. Deaver, B.S. & Fairbank, W.M. (1961). "*Experimental Evidence for Quantized Flux in Superconducting Cylinders*". *Physical Review Letters*. **7** (2): 43–46.
- 29. Doll, R. & Näbauer, M. (1961). "*Experimental Proof of Magnetic Flux Quantization in a* Superconducting Ring". Physical Review Letters. **7** (2): 51–52.