Mechanism of Superconductivity: A Theory

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Abstract

On a microscopic scale, resistivity during electric conduction is caused by collisions of the conduction electrons with the obstructing atoms or molecules of the conductor material, resulting in heat production. Based on this fundamental understanding, a new hypothesis is proposed, which suggests that for superconductivity (i.e., with zero resistivity) to occur, the conductor must have nano-sized straight vacuum tunnels inside with radius large enough to allow the passage of the conduction electrons in a ballistic manner without collisions. In addition, some of the composite atoms of the conductor should be able to readily release electrons to form the conduction band. This hypothesis is supported by experimental observations in the literature, and also offers a plausible explanation for some poorly-understood experimental phenomena observed in the past. The hypothesis also offers practical strategies for the rational design of electric conductors with (quasi-)superconductivity. Lastly, the new hypothesis readily suggests a mechanism for neural microtubule-mediated electrical quasi-superconductance in the nervous system.

1. Introduction

Superconductivity is a unique phenomenon discovered by Heike Kamerlingh Onnes in 1911 by demonstrating the disappearance of resistivity of mercury at temperatures below 4 K [1]. Superconductivity research has attracted intense interest in the past few decades as advances in this technology may have vast scientific and utility potentials. The widely-accepted superconductivity theory, i.e., the Bardeen-Cooper-Schrieffer theory [2], posits that the spin-paired pairs of conduction electrons (commonly referred to as the Cooper pairs) are formed in the metal conduction band. One of the electrons in the Cooper pair may electrically distort the molecular structure of the superconducting material as it moves through, creating nearby a short-lived concentration of positive charge. The other electron in the pair may then be attracted toward this positive charge. It has been suggested that such coordination between electrons can prevent them from colliding with composite molecules of the conductor and thus eliminate electrical resistance. Based on this theory, when temperature decreases, the number of Cooper pairs would, in principle, increase, and ultimately the superconductor becomes a fully spin-paired, diamagnetic system. The theory had helped to explain the pre-1986, lower temperature superconductors, but failed to adequately explain some of the other unsolved problems, such as the scientific meaning of the superconducting critical temperature $T_c$, the high-temperature superconductors, and the superconductivity of carbon-based nanotubes or graphene sheets. In this communication, a new theory is proposed to explain the mechanism of superconductivity.
2. Hypothesis

On a microscopic scale, it is accepted that resistivity is caused by collisions of the conduction electrons with the obstructing atoms or molecules in the conductor material, which results in heat production and increase in conductor temperature. Based on this fundamental understanding, a new hypothesis is proposed here which suggests that for superconductivity to occur, the conductor should meet the following two conditions:

i. The conductor must have nano-sized straight vacuum tunnels inside with radius large enough to allow direct, free passage of the conduction electrons in a ballistic manner without collisions (i.e., zero resistivity). A number of factors, such as atomic composition, lattice structure, temperature and external pressure, would all affect the real size (effective radius) of the conduction tunnels which would then affect superconductivity. The influence of these and also other factors on the conduction tunnels and superconductivity is discussed in section 3.

ii. The composite atoms of the conductor need to be able to facilely release electrons to form the conduction band, which often is achieved through incorporation of certain metallic atoms [3], although certain non-metallic molecules can also readily release electrons for this purpose (such as in the case of neural microtubules as discussed later). This requirement is not special for superconductivity, as this is also required for other forms of electric conduction. However, if the conductor material cannot facilely release electrons to form the conduction band, then superconductivity will be difficult to achieve even when perfect vacuum tunnels are present in the conductor for collision-free passage of the conduction electrons.

3. Evaluation of the hypothesis and the supporting evidence

As briefly discussed below, the proposed hypothesis agrees well with key experimental observations in the literature, and can also be used to provide a plausible explanation for some poorly-understood experimental phenomena observed in the past.

3.1. Superconducting critical temperature \(T_c\)

Superconductivity often is more readily observed at ultra-low temperatures (near 0 K). The reason for this phenomenon is because at ultra-low temperatures, the atomic movements (such as agitation and vibration) of the conductor's composite material will be close to none, i.e., literally static. Let us assume that there are nano-sized straight vacuum tunnels existed in the lattice structure of a given conductor at near 0 K when the composite atoms are almost completely static, and that the radius of these conduction tunnels can allow collision-free passage of the conduction electrons in a ballistic manner (as depicted in Fig. 1a). Under such conditions, the degree of atomic movements, which increases with increase of temperature, would gradually reduce the size (i.e., the effective radius) of the conduction tunnels and eventually may begin to partially obstruct the existing tunnels for collision-free passage of the conduction electrons (Fig. 1b). The degree of obstruction would depend on two main factors: the initial size (i.e., the radius) of the straight static tunnels at near 0 K, and the magnitude of the atomic movements of the conductor material at a given temperature above 0 K. Whereas the former is a build-in structural characteristic of the conductor material,
which is determined by its atomic composition and unique lattice structure, the latter (i.e., the magnitude of atomic movements) would be jointly determined by the internal atomic/molecular structures of the conductor, temperature and external pressure. If we assume that at or above a certain temperature when the atomic movements of the conductor's composite material would reach a degree that begins to diminish the effective radius of the straight conduction tunnels and thereby starts to abolish the collision-free passage of the conduction electrons, then this temperature would theoretically be very close to what is commonly referred to as the superconducting critical temperature, $T_c$, for a given superconductor. Stated differently, at or near $T_c$, the radius of the straight vacuum tunnels would have the minimally-required radius ($R_m$).
for collision-free passage of the conduction electrons. At temperatures below $T_c$, the degree of atomic movements in the conductor material will be smaller, meaning that the effective radius of the straight conduction tunnels would be larger than the minimally-required radius $R_m$ for the resistance-free passage of the conduction electrons, thus facilitating superconductivity at all temperatures below $T_c$. However, at temperatures above $T_c$, the higher degrees of atomic movements of the conductor material likely would narrow down the effective radius of the electron passage tunnels, thereby abolishing superconductivity.

It is of note that at or near the $T_c$ for a given superconductor, the minimal radius $R_m$ of the straight vacuum tunnel required for collision-free electron passage may vary depending on the de Broglie wavelength ($\lambda$) of the conduction electrons ($\lambda = h/p$, where $h$ is the Planck constant and $p$ is an electron’s momentum) in that superconductor. According to the classical approximations for momentum $p$ ($p = mv$, where $m$ is the mass of an electron and $v$ is its conduction speed) and kinetic energy $K$ ($K = \frac{1}{2} mv^2$), the wavelength of a conduction electron can be estimated according to its kinetic energy value. For a conduction election with a kinetic energy $K$ in the range of 1–10 eV, its estimated wavelength would be 1.23–0.39 nm. At higher kinetic energy levels ($K > 10$ eV), the wavelength of the conduction electrons would be shorter than 0.39 nm. As higher electric potential would increase the speed and momentum of the conduction electrons and shorten their wavelength, this might explain why higher electric potential (within a certain range) usually would facilitate the establishment of superconductivity if the temperature is maintained constant; however, when the conduction speed of the electrons becomes too high, it may also increase the potentials for collisions ($i.e.$, increasing resistivity).

### 3.2. Structural properties of superconducting materials

Understandably, some of the conductors may indeed meet the above-proposed two conditions for being superconductors, $i.e.$, they contain the electron-releasing atoms or molecules, and they also happen to contain straight vacuum tunnels inside which can allow collision-free electron conduction. However, the chances for the presence of straight, collision-free tunnels for conduction electrons inside a naturally-existing conductor likely are quite low, and this might be the reason why many naturally-occurring conductors cannot function as superconductors under whatever experimental conditions. Based on the above explanation, it is understood that some superconductors may happen to contain larger vacuum conduction tunnels inside their lattice structures, $i.e.$, their radius at near 0 K is far greater than the minimally-required radius ($R_m$) for superconductivity. As such, these superconductors would have much higher $T_c$ as the radius of their electron passage tunnels can still allow collision-free passage of the conduction electrons even under conditions in which the composite atoms of the conductor are having much higher degrees of vibrational movements due to higher temperatures.

It is of note that the metallic atom barium (Ba) has been among the most widely-used elements for making superconducting materials (reviewed in [3]). The higher rate of past success with Ba likely is because this element has a relatively large atomic radius. When it is used in combination with other smaller metallic or non-metallic atoms, it has a higher chance of creating suitable lattice structures that may leave large-enough straight conduction tunnels inside, thus enabling the collision-free electron conduction (as schematically depicted in Fig. 1a). To put it figuratively, if one tries to
stack a large number of different-sized balls together according to certain repetitive stacking rules, the chances of successfully creating large-enough straight passage tunnels within this large stack of balls would be far greater if one tries to stack a proper ratio of large-size balls \((e.g., \text{basket balls})\) with smaller balls \((e.g., \text{tennis balls})\; \text{the small balls usually function as structure-stabilizing bonding elements or as facile electron releasers}\), as opposed to stacking all small balls together \((e.g., \text{tennis balls} \text{or ping-pong balls}; \text{either in certain mixture or just a single type of balls})\).

The above concept is in line with many past experimental observations. One example is the case of pure copper, which is an excellent regular conductor but cannot become superconducting even at very low temperatures. The main reason likely is because copper atoms have a very small atomic radius, and when they are stacked tightly together, the lattice structure \([4]\) likely would not be able to leave large-enough straight tunnel spaces inside for collision-free passage of the conduction electrons \((\text{as schematically depicted in Fig. 1c})\). In contrast, many of the well-known superconducting materials were usually made of a combination of large and small atoms that have their crystal lattice structures favoring the formation of large passage tunnels inside. For instance, the classic perovskite oxide \(\text{SrTiO}_3\) \([5]\) made in 1964 consists of two large-size atoms and one small oxygen, which leaves considerable tunnel space in its crystal lattice structure. Similarly, several other well-known superconducting materials, such as \(\text{YBa}_2\text{Cu}_3\text{O}_7\), \(\text{La}_2\text{CuO}_4\) and \(\text{MgB}_2\), all appear to have unique crystal lattice structures that favor the formation of sizable passage tunnels within \(\text{(discussed in [3])}\). Certainly, it will be of considerable interest in the future to model and also experimentally determine the passage tunnels contained in these superconducting materials.

In this context, it is of note that the metallic element cesium \((\text{Cs})\), which has an even larger atomic radius than \(\text{Ba}\), theoretically would be an excellent choice for making superconducting materials \([6]\). However, this element is chemically not as stable compared to \(\text{Ba}\), which might have limited its practical use in some instances.

Lastly, it is of note that the free hydrogen atoms, which are the smallest atoms with a facile tendency to release their single electron, when tightly stacked with relatively larger atoms through chemical bonding and/or under super-high pressure, may produce suitable lattice structures that would allow the collision-free electron conduction within the conductor. The hydrogen atom is suitable for this type of experimental design because after its single electron is released to form the chemical bond or join the conduction band, the remaining proton will be even much smaller than the hydrogen atom, thereby potentially leaving more space for the collision-free passage of the conduction electrons. This intriguing possibility is in line with a number of recent experimental observations \((\text{discussed in [7, 8])}\).

### 3.3. Effect of high pressure on superconductivity

In the past decade or so, there have been a number of studies demonstrating that under conditions of super-high external pressure, superconductivity could be more readily observed, even at high temperatures \([9–12]\). Based on the hypothesis proposed here, it is understood that the super-high external pressure can help establish superconductivity because it can significantly limit the vibrational movements of the conductor’s composite atoms. With this understanding, the high pressure likely would have a similar actual effect as the ultra-low temperatures, and both could help reduce the vibrational movements of the composite atoms that form the straight electron
passage tunnels, thereby facilitating the establishment of superconductivity.

In this context, it is of note that inside the earth’s core, there is a buildup of enormous heat and pressure, due to the huge mass of the earth lying on top of it. Although the high temperature would greatly increase the tendency of atomic movements, these movements likely are suppressed by the overwhelming high pressure exerted toward the earth’s core by the mass of the earth. As such, some of the superconducting compounds formed naturally inside the earth’s core would be favored to exhibit superconductivity under the favorable high pressure conditions. In addition, the high temperatures at the earth’s core would facilitate the release of electrons to form the conduction band. Jointly, these unique conditions at the earth’s core would favor the formation of superconductivity, which might explain why the earth is a strong and giant magnet.

3.4. Carbon nano-devices as (quasi-)superconductors

Graphite is a layered material made of carbon sheets, and each layer of the carbon atoms was tightly packed in a two-dimensional honeycomb crystal lattice, called graphene [13]. Carbon nanotubes, discovered by Iijima in 1991 [14], have scroll-type structures (4–30 nm in diameter) and are commonly referred to as multi-walled nanotubes. In comparison, the single-wall nanotubes usually have a size of approximately 1 nm in diameter. Earlier studies have surprisingly found that carbon nanotubes and graphene sheets are good conductors [15, 16], whereas diamond, which is also made of carbon, is a good insulator. In light of the proposed new hypothesis, it is understood that in the case of carbon nanotubes, the conduction electrons released inside by doped elements or introduced into these straight vacuum nanotubes would be able to move in a ballistic manner and essentially collision-free, which is similar to the conduction electrons moving collision-free through the vacuum conduction tunnels inside a metallic superconductor. It is expected that the conduction electrons may also be able to move similarly in a ballistic manner and essentially collision-free through the suitable vacuum spaces between the two adjacent graphene sheets.

It is known that with regular metal conductors, temperature increase is mostly associated with increased resistivity. However, in most cases of carbon nanotubes or graphene sheets, resistivity decreases with increasing temperature [13]. This intriguing discrepancy can be readily explained on the basis of the new hypothesis. In the case of normal metal conductors, it is known that temperature increase would increase the movements of metallic atoms, which would then increase collisions of metallic atoms with the conduction electrons, resulting in increased resistivity and heat production. By contrast, in the case of carbon nanotubes and graphene sheets, the size (or space) of the vacuum electron passages are usually far larger than those formed inside normal metallic conductors or superconductors, and as such, an increase in temperature (which is associated with increased movements of atoms that form the nanotubes or graphene sheets) may not cause a drastic narrowing of the effective radius of the nanotubes or of the effective vacuum space between the two adjacent graphene sheets in such a manner that would abolish superconductivity. On the other hand, increased temperature would facilitate the release of electrons to form the conduction band, which would actually increase conductivity. Therefore, the net effect of temperature increase in the cases of carbon nanotubes or graphene sheets would be associated with increased conductivity.

Similar to carbon nanotubes and graphene sheets, superconductivity has also been
observed in a number of fullerene-based materials, including the well-known C60 Buckminster balls doped with certain metallic elements [17]. The fact that fullerene-based materials, along with carbon nanotubes and graphene, which are all carbon-based structures containing ample nano-sized vacuum spaces inside and are superconductors, clearly suggests that the presence of suitable vacuum spaces (tunnels) in the structure for collision-free electron conduction is a critical requirement for superconductivity.

In 2007, Novoselov et al. [18] discovered the room-temperature quantum Hall
effect in graphene. It was suggested that the observation was due to the highly unusual nature of charge carriers in graphene, which might behave as massless relativistic particles (Dirac fermions) and move with little scattering under ambient conditions [19, 20]. In light of the proposed hypothesis, the observation appears to clearly indicate that the conduction electrons can move in a ballistic manner and mostly collision-free within the two adjacent sheets of graphene.

3.5. Neural microtubules as a physiological quasi-superconductor

It is known that the nervous system (brain in particular) has enormous amount of neuro-electrical activities taking place almost all the time, even during sleep. Unlike man-made electronic devices (such as computers), the nervous system surprisingly never suffers from “overheating” due to its overwhelming amount of neuro-electrical transmission. Based on the new explanation on (quasi-)superconductivity tendered above, it is hypothesized that the neural microtubules (neuro-MTs) which are major internal structural components of axons and dendrites may function as unique nano-sized bio-devices that can mediate electrical transmission with quasi-superconductivity. Neuro-MTs are hollow cylindrical tubes (with an outer and inner diameter of ~25 and 14 nm, respectively) [21], consisting of 13–15 rows of filaments [24, 25] made of α- and β-tubulin heterodimers [22, 23] (depicted in Fig. 2a). Notably, there are two types of microtubule lattice structure: the A-lattice has rotational, helical symmetry, and the B-lattice has a physical discontinuity known as a seam [21]. It is hypothesized that the neuro-MTs contained in nerve fibers are symmetric cylindrical nanotubes without a seam, such that it can better maintain their strong vacuum hollow structure inside suitable for collision-free electrical transmission (Fig. 2a).

The α/β-tubulin heterodimer is known to be an electric dipole, with a high negative electric charge of ~23e and a large intrinsic high dipole moment [26, 27]. Like other dipoles, MTs in solution can readily align with applied electric fields [28]. It is of note that because of this unique dipole arrangement, the inner surface of a neuro-MT actually contains consecutive positively-charged and negatively-charged cylindrical structures.

It is known that the inner part of a nerve fiber or an axon (i.e., its cytosolic compartment) is negatively charged (approximately −70 mV). The outer surface of neuro-MTs is also negatively charged as the C-terminal tails of α- and β-tubulins contain several acidic residues which are located on the outer surface (reviewed in [29]). The inner surface of a neuro-MT is even more negative, as it can serve as a high-capacity electron-storage device [30, 31]. Neural stimulation in the form of action potentials occurring at neural cell membrane will activate Na+ channels, resulting in Na+ influx. An increase in cytoplasmic Na+ at or near a neuro-MT resulting from an action potential would be functionally similar to directly applying an electric field (or voltage) to a neuro-MT, triggering the release of electrons stored inside the neuro-MT, and electrons will move toward where the AP is initiated (Fig. 2b). It is hypothesized that the conduction electrons formed inside the vacuum neuro-MT would have the following characteristics:

1. The conduction electrons will be moving in a ballistic manner in the center of the hallow MT, due to the circular forces exerted eveny on the conduction electrons by the consecutive cylindrical dipoles (made of α/β-tubulin heterodimers). Because neuro-MTs
are vacuum in nature, the conduction of electrons inside the MTs would be collision-free (i.e., superconductivity) (Fig. 2b).

ii. Owing to the presence of consecutive dipole ring structures of the neuro-MTs (as depicted in Fig. 3a), the speed of the conduction electrons in each neuro-MT expected to be far slower than usual, as the two neighboring rings (one positively-charged and one negatively-charged) will each exert a force on the conduction electrons and slow down their moving through each positively-charged ring. Despite the slow conduction speed, it should be noted that the speed by which an electric current is established throughout the entire length of a neuro-MT will not be affected at all; theoretically, the speed will be equal to the speed of light. This unique feature will enable physiological neuro-electrical transmission to occur with super-high efficiency as only minimal numbers of the conduction electrons will actually pass through a neuro-MT in unit time. Even if we assume that the kinetic energy $K$ of a slow conduction electron is as low as 0.1 eV, its

Figure 3. Effect of the consecutive dipole-ring structure on electron conduction inside a neuro-MT. As depicted in a, when a conduction electron is right at the center of the positively-charged ring 3, all the forces generated by the neighboring dipole rings 1–5 that act on the electron will be cancelled out. However, when the electron is in between the positively-charged ring 3 and the negatively-charged ring 4 as schematically depicted in b, the forces generated by the neighboring rings will strongly slow down its conduction through a positively-charged ring to the next positively-charged ring. Note that the length of each arrow is drawn proportional to the exact magnitude of the calculated force. In addition, as soon as the neural stimulation (i.e., the AP or voltage) disappears, the electron conduction will come to a complete stop almost instantaneously, and the conduction electrons would be forced to stop exactly where the positively-charged ring is. Here it is tempting to also speculate that the electrons might be “floating” right at or near the center of a positively-charged ring structure.
estimated wavelength (\(\lambda\)) would be 3.88 nm, which is still smaller than the inner radius (~7 nm) of a neuro-MT. This is probably why neuro-MTs have a relatively large inner radius size, as it would enable the conduction of electrons with very low speed in neuro-MTs and thereby would help to conserve cellular energy (Fig. 3a).

iii. The presence of the consecutive cylindrical dipole structure inside a MT also helps to terminate the conduction band with exceptional high efficiency, \(i.e.,\) as soon as the neural stimulation (in the form of an action potential) ends (explained in Fig. 3b). This unique feature is fully in line with the known characteristics of physiological neuro-electrical activities (for instance, the voluntary muscle movements can be initiated at will almost instantaneously, and they can also be terminated immediately without any lingering after-effects). Because of this unique feature, the collision-free electric conduction occurring inside a neuro-MT is considered quasi-superconductivity in nature.

iv. As aforementioned, neuro-MTs can serve as a high-capacity charge storage device [30, 31]. The large capacitance of neuro-MTs for electrons is a crucial feature which would enable them to fulfill the vital physiological function of mediating enormous amount of neuro-electrical transmissions.

4. Concluding remarks

It is hypothesized that for (quasi-)superconductance to take place, the conductor must have straight vacuum tunnels inside with effective radius size large enough to allow essentially collision-free passage of the conduction electrons in a ballistic manner. The proposed hypothesis is in agreement with many experimental observations, and also offers a plausible explanation for some poorly-understood experimental phenomena of the past. Based on the new hypothesis, a plausible mechanism is proposed for neuro-MT-mediated electrical quasi-superconductance in the nervous system.

The proposed hypothesis may also offer some practical suggestions for the rational design of (quasi-)superconductors for research and industrial uses. For the more traditional element-based superconductors, it might be possible in the future to rationally design (or virtually screen for) unique three-dimensional metallic lattice structures that may contain suitable vacuum tunnels inside for collision-free electric superconductance. On the other hand, in the cases of carbon nanotubes or graphene sheets, future efforts are needed to improve the fabrication techniques to ensure the production of uniform vacuum nanotubes with sizes properly suited for electrical superconductance. Similarly, it is expected that future conducting devices based on graphene sheets will also be of similar values, but technological advances are needed to obtain uniformity and optimal thickness (and size) of the vacuum spaces between the two adjacent sheets. It is expected that when multi-layered graphene sheets (with optimal vacuum spacing) are evenly stacked up, or multiple graphene sheets are rolled up to form multi-walled nanotubes, superconductance (or quasi-superconductance) may occur inside the ample vacuum spaces of the multi-layered structures. Lastly, it is of note that not all perfectly-fabricated carbon nano-conducting devices can serve as good conductors. The ability to firmly and evenly incorporate charge-producing composite elements inside the vacuum nanotubes or between the graphene sheets is another challenge that we need to overcome before carbon-based nano-devices may reach their full potentials for future use as (quasi-)superconducting devices. Similarly, it
is expected that other atomic elements (e.g., silicone) will also be widely used in the future in place of carbon in similar nano-devices with (quasi-)superconductivity.

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Conflict of Interest

The author declares no conflict of interest.