Superconducting principles

Baihua Qi and Tian Qi

Email: qibh@yahoo.com

Abstract

This paper explores superconducting principles. Whether a substance is a superconductor depends on whether it has a global electron energy level orbit.

Superconductivity： H. Kamerlingh Onnes [1] Discovered some materials exhibit zero resistance at a certain temperature， Meissner-Osenfeld [2] Discovered completely diamagnetic while being zero resistance.

Basic phenomenon:

1. When the temperature is lower than a certain critical temperature $\mathrm{T_c}$, objects become superconducting: resistance is zero。And there is the Meissner-Osenfeld effect: Completely diamagnetic.
2. When the temperature is higher than $\mathrm{T_c}$: $\frac{T}{\mathrm{T_c}} > 1$, superconductivity disappears; Or when the external magnetic field is greater than a certain magnetic field $\mathrm{B_c}$: $\frac{B(T)}{\mathrm{B_c}} > 1$, superconductivity disappears either; or when temperature plus magnetic field consistent with $\frac{\mathrm{H}(T)}{\mathrm{H_c}} + (\frac{T}{T_c})^2 > 1$, superconductivity disappears; And when $\frac{\mathrm{H}(T)}{\mathrm{H_c}} + (\frac{T}{T_c})^2 \leq 1$, superconductivity occurs.
3. The critical temperature of many superconductors changes synchronously with the critical magnetic field. Basically if a superconductor's T_c is higher， its $\mathrm{H_c}$ is higher too， and vice versa. There are also some superconductors that are very sensitive only to external magnetic fields, we will not discuss this type of superconductor for now.
4. It can transform certain substances into superconducting substances when applying external pressure and it can improve the superconducting properties of certain superconducting materials by increasing superconducting temperature. A direct physical effect of external pressure is to compress the distance between atoms. This clearly shows that the distance between atoms is critical for superconductivity.
5. There is a Josephson Effect.
6. There is a mutation in the electron heat capacity before and after the superconducting state disappears, which clearly indicates that there is an energy gap and the energy gap needs to be overcame when a superconductor transforms into a non-superconductor. Because superconducting electrons need to absorb energy when they transform into ordinary electrons, the heat capacity of the superconductor will suddenly change downward. After more electrons are converted into normal electrons they will participate in thermal motion and contribute to the heat capacity as free electrons.
7. Good electrical conductors are non-superconductors. Semiconductors or poor conductors or even insulators could be superconductors.
8. Superconductivity is also related to the lattice structure of substances. The same substance has different superconducting critical temperatures due to different lattice structures. Therefore, the origin of superconductivity must be related to the lattice structure of substances.

9. Low-temperature superconductors have isotope effect, $T_c M^{\alpha} =$ constant, $\alpha = \frac{1}{2}$, because $T_c \propto \theta_D$, and $\theta_D \propto M^{-\frac{1}{2}}$. This effect does not always hold.

Three factors affect superconducting state：

1. Temperature： Superconducting phenomena can occur in materials only below a certain ambient temperature, and above that, superconducting completely disappears. This temperature is called critical temperature T_c. The critical temperature of each material is basically stable and consistent. The role of temperature is to manifest superconductivity and destroy superconductivity.
2. Magnetic field: Superconducting can be destroyed by applying an external magnetic field to a certain intensity. It is called the critical magnetic field B_c or H_c, and its function is similar to temperature. Correspondingly, there is a critical current I_c, which has the same physical meaning as B_c.
3. Pressure: External pressure can make materials that cannot obtain superconductivity only by lowering the material temperature become superconducting materials, and it can also increase the critical temperature of superconducting materials. It is conceivable that decompression can destroy superconductivity.

Temperature and pressure are thermodynamic quantities, and meanwhile magnetic field is an electromagnetic quantity. Superconductivity is obviously an electromagnetic phenomenon. The above three factors are in the field of thermodynamics or electromagnetism and participate in different physical processes. The temperature and pressure which participate thermal processes affect the electromagnetic properties of materials, which is the key to understanding superconductivity.

Furthermore, among the three factors, pressure is the most important and essential because pressure can transform non-superconducting substances into superconducting substances and improve the properties of superconducting substances. The decreasing temperature only displays and triggers the superconducting state. Increasing temperature and applying an external magnetic field can destroy the superconducting state. Therefore, the two thermodynamic physical processes of pressurization or decreasing temperature respectively have the same effect on a certain electromagnetic property of materials, and this electromagnetic property is the origin of superconductivity. Moreover, this electromagnetic property can also be affected and destroyed by an external magnetic field. Since the superconducting state is related to the lattice structure of the material and the critical temperature and critical magnetic field of the same material are different due to different lattice structures, therefore the electromagnetic property of materials must also be related to the lattice structure of the material.

The second basic phenomenon of superconductivity deserves more careful study. The formula can be expressed as $f(B) + g(T) \leq c$, where c is a specific physical quantity that has nothing to do with the outside environment(temperature or magnetic field) and is only related to the composition and structure of superconducting materials themselves, and $c > 0$. $f(B)$ is a function only related to the external magnetic field, and $c \geq f(B) \geq 0$. $g(T)$ is a function only related to temperature, and $c \geq g(T) \geq 0$. This is one of the few superconducting relationship formulas that can be expressed in a clear mathematical expression. It is the key point to understanding the superconducting phenomenon. It is this physical quantity c that determines whether the material is a superconductor, as well as the superconducting critical temperature and the critical magnetic field. Understanding what is c will be helpful to understand superconductivity. In principle, the presence of several different physical quantities in a mathematical formula means that the terms in the formula have the same dimensions and, although involved in different physical processes, act on the same physical quantity and have the same physical effect. The term g (T) related only to temperature and the term f (B) related only to magnetic field can appear in a mathematical formula and appear in the form of addition, which indicates that the process of increasing and decreasing temperature in thermodynamics and the process of increasing and decreasing magnetic field in electromagnetism can Act on specific physical properties of materials and have the same physical effect on the materials and they can produce the physical effect individually or jointly. But they do not affect each other. Increasing or decreasing temperature does not affect the external magnetic field. Similarly, increasing or decreasing magnetic field does not affect the temperature.

The third basic phenomenon of superconductivity: the synchronous growth of the critical temperature and critical magnetic field of many superconductors indicates that the critical temperature and critical magnetic field of superconductors are both controlled by a specific property of the superconducting material. If the value of this property of the superconductor is large, the critical temperature and critical magnetic field of the superconductor will be large. If the value of this property of a superconductor is small, the critical temperature and critical magnetic field will be small. Therefore, the relationship between the critical temperature and critical magnetic field of superconductors can also be established.

Explanation of superconductivity：

1. Non-resistant current and complete diamagnetism: The essence of superconducting Non-resistant current is not that electrons flow without resistance, but that electrons flow without energy loss. Therefore, it is not a zero-resistance ideal conductor, but a energy lossless conductor. If there is acceleration in normal electron motion, there will be energy loss due to radiation, and eventually the motion will stop. Superconducting electrons can move without any energy loss and this is a quantum behavior, just like the quantum effect when electrons move around an atomic nucleus. This quantum effect is provided by the atomic nucleus. The current of a zero-resistance ideal conductor requires external energy to be maintained to keep the current. Once the external energy is withdrawn, the current will disappear. When the current disappears, there will be no paramagnetic or diamagnetic response to the external magnetic field. Once the current in a energy lossless conductor occurs, it can be maintained by itself without external energy. This is the difference between quantum behavior and non-quantum behavior. At the same time, diamagnetism is an essential property of any atomic orbital electron, and the nuclear orbital electrons must respond to an external magnetic field. The premise is that the electrons orbiting the nucleus have energy to move, and this energy will always exist because this energy is a quantum effect provided by the atomic nucleus. Superconducting electrons are in the quantum effects provided by lattice atoms rather than just single atomic nuclei. Their Non-resistant movement and diamagnetism are the respective embodiments of the electric field effect and magnetic field effect of the lattice quantum effect. They are two sides of the same thing and they are related and cannot be split. Whether there is a single electron or a pair of electrons in the orbit is not the core issue. The core issue is that electrons can move

without energy loss. This is the quantum behavior of electrons moving at a certain orbital energy level.

2. Pressure can change the superconducting properties of materials. It turns non-superconductors into superconductors, and can also improve the properties of superconductors. What pressure changes can reveal the nature of superconductivity. A direct effect of pressure is to shorten the distance between atoms of material.
3. Superconductors are controlled by temperature and magnetic field. Two completely different physical processes can produce similar physical results: temperature and magnetic field can affect the state of superconductors separately or jointly. They have a linear superposition relationship and are also strongly affected by pressure. The critical temperature and critical magnetic field change synchronously, which indicates that a specific property of the superconductor determines the critical temperature and critical magnetic field, and this specific property also determines whether the material is a superconductor, and when it enters or exits the superconducting state.

The cause of superconductivity

The commonality of the consequences of the above three factors should be the cause of superconductivity. Among them, the existence of global atomic orbits in the material is the possible common point of the three factors: global atomic orbits can allow superconducting electrons to have quantum effects. That is, they have energy levels to maintain a state of motion. This state of motion can also move without losing energy. The state enables the superconducting electrons to continuously resist the external magnetic field and thereby produce complete diamagnetism. Temperature can affect the electrons in the orbit, and increasing the temperature can destroy the electronic state of the orbit, while decreasing the temperature can stabilize the electronic state of the orbit; external magnetic field can destroy the electronic state of the orbit; external pressure can also stabilize the electron state of the orbit state. Electrons can move in this orbit without losing energy, just as electrons can move in atomic orbits without losing energy. This orbit should be the ground state of the atom, or it can be a low-order excited state as long as they can be connected into a global orbit [called a superconducting orbit]. This orbit is mainly determined by the atomic structure of the material plus the crystal structure [if it is a solid crystal]. The distance between atoms [lattice distance] must be close to the diameter of the orbit, so that the superconducting orbits between adjacent atoms are connected, causing the orbit to become a global orbit. Electrons can move across individual atoms in the entire material although locally the electrons still move in atomic orbits; and higher-order orbits cannot form global orbits due to the space limitations of the material structure [called superconducting excited states, or non-superconducting excited states. superconducting state]. This is a necessary condition for a material to become superconducting. It is a known physical phenomenon that an electron's energy level can span two atoms, i.e. covalent bonding, and there is no physical limitation that prevents an electron from spanning more than one atom.

Among the three factors that affect the superconducting state, pressure is the core factor. It leads to the emergence of superconductors and improves superconducting property. Temperature only makes the superconducting state appear or disappear. A drop in temperature does not cause a superconducting state but leads material turning into a superconducting state. The external magnetic field is completely destructive. Its destructive effect is parallel to and independent of the temperature increase and the effects are linearly superimposed. Understanding the phenomenon of superconductivity starts with understanding the physical consequences of applying pressure to an object, and verifying why temperature and magnetic field have the same physical effects. Pressurization shortens the lattice spacing and brings the atomic spacing closer, connecting the inter-atomic orbital into global orbits. It can also overlap the already connected orbital to promote the formation of superconducting states and enhance superconducting properties such as increasing the critical temperature. This is why applying pressure can turn non-superconductors into superconductors.

A global orbit must exist to allow electrons to move unimpeded throughout the object and this orbit provides energy which is macroscopic quantum effects to allow the electrons to always be in motion in this orbit. Therefore, once an external magnetic field is applied, the electrons can react to the external magnetic field and produce a complete Diamagnetic field. External magnetic fields have no effect on stationary electrons and so superconducting electrons must have energy to produce diamagnetic effects against external magnetic fields. The movement energy of electrons can only come from the quantum effects provided by the atomic nucleus just like the movement of electrons on the original path of atoms. The whole process is exactly the same as the diamagnetic process of atoms. The atomic nucleus provides the energy level of the electrons in the nuclear orbit. The electrons with energy level must resist the external magnetic field. The difference is that the number of electrons in an atom is limited and can only produce limited diamagnetism while a superconducting electron has a large number and can provide complete diamagnetism. Non-resistant conduction and complete diamagnetism are two aspects intrinsically related to the superconducting state. The existence of a global orbit requires that the physical position of the orbit is in the middle of the lattice. That is, the orbit diameter is close to the lattice distance, and it would be better if it can overlap. The degree of being close to between the orbit and the lattice is related to the composition and lattice structure of the substance.

This orbit requires:

1. Non-local, periodic on the lattice.

2. The superconducting ground state is the atomic ground state, or it can be the atomic excited state, or it may even be composed of several atomic orbits as long as they are global orbits [called superconducting orbits]. If the excited state of atoms constitutes the superconducting ground state orbit, then the superconductor has two critical temperatures : T_{c1} and T_{c2}. When $T_{c1} \leq T \leq T_{c2}$ then the material is in the superconducting state. Because the atomic ground state is not a superconducting state, the temperature decrease causes the electrons to fall back to the ground state of the atom and because the ground state of the atom is not a superconducting state and therefore the material loses superconductivity. The temperature at which material enters the ground state of the atom is T_{c1}. For normal superconductors, T_{c1}=0.

The destruction of the superconducting state is when the ground state electrons are excited by the environment [temperature or magnetic field] to a higher energy level state, or a lower energy level, and the higher energy level or lower energy level is not global connected. Especially when the energy difference between the superconducting ground state and a higher energy level or a lower energy level is very small it is easier to be excited by the environment and has a few probability to be fixed at a certain energy level state. A large energy range difference is an important condition for maintaining the superconducting state. Otherwise, a slight change in the temperature of the environment can destroy the superconducting state and make the material unstable even if it is in the superconducting state. Another factor is that superconducting orbits overlap with atomic orbits, which can also stabilize the superconducting state.

3. Zero resistance and diamagnetism are two sides of the same coin: there are superconducting orbits and there are electrons in the orbit. The electrons cannot stop and must move at a certain speed and energy. Since there is an the orbit and when an external voltage is applied electrons must flow in one direction to produce a macro current with zero resistance [electrons are inherently moving without energy consumption with no specific direction and so no macro current is apparent to the outside]; If there is no resistance and no energy consumption electrons moving and when applied external magnetic field the electrons field, will inevitably produce an induced magnetic field to resist the external magnetic field.

4. There are superconducting excited states. When electrons are in the superconducting excited state, they become normal electrons and can conduct electricity but they will jump from each atomic excited state, causing resistance and heat. Superconducting excited states are local. There is a sudden change in the electron heat capacity from the superconducting ground state to the superconducting excited state because superconducting electrons will absorb energy and then participate in thermal motion after becoming non-superconducting electrons. This transition of electrons is a sudden phase change of a large number of electrons. The energy level difference from the superconducting ground state to the excited state is a key factor in determining the critical temperature. If the energy difference is not large, the finite temperature can excite electrons to transition from the superconducting ground state to the excited state, thus destroying superconductivity. Since the superconducting ground state and excited state are certain atomic states of atoms, atoms with a large energy range from the ground state to the first excited state are favorable conditions for increasing the superconducting temperature of objects such as hydrogen atoms.

5. Whether the superconducting current body is a boson is not the key. There are multiple states in the superconducting ground state that can accommodate multiple electrons, just like the higher-order states outside the nucleus can accommodate multiple electrons. Furthermore, each crystal lattice only has one or two For metallic electrons and there is no need to worry about fermions not getting along. The electrons in the superconducting ground state will also be at their lowest energy level and they are naturally in pairs with opposite spins.

6. The material appears superconducting after being pressurized, which indicate that superconductivity is related to the density of the material. That is, superconductivity is related to the lattice distance. After pressurization, the atomic diameter and the lattice distance are closer which makes the disconnected orbit connected. Pressurization can also cause the orbit to overlap with the lattice, which results the higher superconducting critical temperature and more stable superconducting state.

7. There are two factors that affect the superconducting state: temperature and magnetic field. It seems that their effects are linearly superimposed and they have the same equivalent effect on superconducting material but they do not affect each other. Magnetic field and thermal motion are

completely different physical processes. Why do completely different physical processes produce the same effect on superconducting material? Energy level is a very likely the affected physical quantity, because external magnetic field and thermal motion can affect the electron energy level at under low temperature conditions. The experimental data shows that the influence consequences are the quadratic of temperature and the linear parabola equation of the external magnetic field and it can be used as identification for any theory about superconductivity.

The lattice structure affects whether adjacent atomic orbits can approach and even overlap, thereby affects whether the object is a superconductor and its critical temperature.

It is those electrons in atomic orbits that are superconducting electrons and participate in superconducting current. This also explains why poor conductors and even insulators which have no free electrons at all are also superconductors because there are electrons in atomic orbits in any material made of atoms. Superconductivity is only conducted by orbital electrons. Free electrons do not participate in superconductivity.

Explanation of basic phenomena of superconductivity

The zero resistance and complete diamagnetism of the superconducting state are two sides of the same thing: the superconducting electrons are originally in the electron orbit of nucleus, and have energy and speed to move continuously in the orbit. When there is no external field, each electron moves in different directions and there is no macroscopic current and the magnetic field generated by the current. Once an external electric field is applied, the electrons will move in one direction. Because the electrons are running in orbits and this is the reason why there is no resistance and the electrons do not lose energy. This is the macroscopic quantum effect of the atomic nucleus on the orbiting electrons. As a result, the orbiting electrons have kinetic energy and this movement does not lose energy. Once an external magnetic field is applied, the electrons running in the orbit will have a current which generates a diamagnetic magnetic field, just like the electrons in nucleus which will have a diamagnetic effect.

Basic formula of superconductivity：$\mathbf{E_b + E_v \le E_1 - E_0 = \varepsilon}$ (1)

This formula is a specific expression of the formula f(B) + g(T) $\le$ c, where E_v is the thermal energy of superconducting electrons, and E_b is the increased in diamagnetic energy of superconducting electrons caused by an external magnetic field, and the external magnetic field causes orbital electrons to be generated by the magnetic field. The diamagnetic energy is usually very complicated. To simplify, assume that the superconducting ground state is the orbital ground state, and the orbit is circular, the orbit radius is r_0, the energy level is ε_0, and the movement speed is v_0, we have $k\frac{qe}{{r_0}^2} = m_e\frac{{v_0}^2}{r_0}$, $k\frac{qe}{2r_0} = \frac{1}{2}m_e{v_0}^2$。 After Applying magnetic field B, the orbit radius is r_0 and the energy level is ε_1， and the movement speed is v_1， $ev_1B + k\frac{qe}{{r_0}^2} = m_e\frac{{v_1}^2}{r_0}$, $\frac{1}{2}ev_1r_0B + k\frac{qe}{2r_0} = \frac{1}{2}m_e{v_1}^2$， $\frac{1}{2}m_e{v_1}^2 - \frac{1}{2}m_e{v_0}^2 = \frac{1}{2}ev_1r_0B = E_b$， E_b is Proportional to the external magnetic field B. E_v is the thermal energy of superconducting electrons。 ε is the difference between the superconducting excited state energy level and the superconducting ground state energy level which is determined by the atomic structure and lattice structure of the object. Energy addition caused by magnetic fields + heat energy addition > energy difference between the superconducting excited state energy level and the superconducting ground state energy level then the superconducting state is destroyed. Superconducting states can also be respectively destroyed by magnetic fields or thermal energy.

The superconducting ground state and the superconducting excited state are both certain energy levels of atoms. The atomic state is squeezed by other atomic nuclei in the crystal lattice and its physical position has greatly deviated from the isolated atomic state and the physical distance between states has become smaller and atoms are closer. The superconducting ground state is easily destroyed by external magnetic fields or heat.

1. Effect of pure heat energy： $E_v = E_1 - E_0 = \varepsilon$。 $E_v = \varepsilon$， which is the energy level difference between the superconducting ground state and excited state. In the superconducting state, the thermal energy of a single superconducting electron effected by temperature is $\int_0^T C_{ev}\,d\tau$， where C_{ev} is the average specific heat of superconducting electrons。 Even though the superconducting electron is in the superconducting orbit, the effect of the nucleus is small. Superconducting electrons can be approximately treated as free electrons， when at low temperature C_{ev} is directly related to the temperature T and at high temperatures C_{ev} is a constant， At general cases C_{ev} is related to T^{α}, where $0 \leq \alpha \leq 1$. So E_v is related to the $T^{\alpha+1}$. The average specific heat is different from the heat capacity of electrons in superconductors. The electron heat capacity curve is in exponential form. It is the heat capacity of the entire electrons. It means that as the temperature increases, there are more number of electrons participating in thermal motion. The number of electrons increases exponentially. Meanwhile the average of each electron specific energy is not exponential.
2. Effect of pure magnetic field： $E_b = \frac{1}{2}ev_1r_0B = \varepsilon$, $B_v = \frac{2\varepsilon}{ev_1r_0}$. The greater the excited state energy level difference, the greater the critical magnetic field.

Further explanation in detail：

1. When the temperature is lower than a certain temperature T_c, the object becomes superconducting and the resistance is zero. The electron enters the superconducting state. The superconducting state is usually the atomic ground state energy level formed by the Schrödinger wave function generated by the substance atomic nucleus plus the electrons in the outermost layer. This energy level is global. Superconducting electrons can move globally with unhindered, just like the movement of electrons in atomic orbits. They have specific energy and are constantly moving in objects. They do not show electromagnetism when there is no external electric field. Once an electric field is applied, the electrons move in one direction without resistance. that is superconducting zero-resistance phenomenon, and the current also generates a magnetic field. Once the temperature exceeds the critical temperature, thermal energy excites superconducting electrons into higher-order energy levels. The higher-order energy levels are not globally connected and the superconducting state will be destroyed. Not all substances have global energy levels or there is a global energy level but electrons cannot reach this energy level, which is the basis for distinguishing superconductors from non-superconductors. The critical

temperature is related to the global energy level and the overlap between the atomic orbits which form global energy level. Usually superconductivity occurs at low temperature. The low temperature has two effects on object: one is to let the electrons in the atomic ground state, which is usually also the superconducting state. That is allowing electrons to enter the superconducting state; Secondly, the material shrinks at low temperature and the distance between atoms is closer, thus promote the atomic ground state to approach the lattice distance and form a global superconducting state. Therefore, the critical temperature is related to the superconducting ground state, and also to the overlap between the superconducting ground state and the atomic ground state. The more overlap between the superconducting ground state and the atomic ground state, the more stable of the superconducting state. Therefore, the more the superconducting ground state and the atomic ground state overlap, the higher the critical temperature. The proximity or overlap of the ground state is closely related to the material composition and lattice structure. Different lattice structures lead to different degrees of proximity or overlap, thus affect the critical temperature. The critical temperature is also related to the electron specific heat. The higher the specific heat, the lower the critical temperature.

2. Meissner-Osenfeld effect. When an electron is in a superconducting state, it keeps moving at a certain energy level. Once an external magnetic field is applied, diamagnetism will appear and it is completely diamagnetic just like the diamagnetism of electrons inside an atom. The difference is that there is enough a large number of superconducting electrons which make it completely diamagnetic. Once the external magnetic field is greater than the critical magnetic field, the superconducting electrons are excited to higher-order energy levels. The higher-order energy levels are not global energy levels and the superconducting state is destroyed just like the above-mentioned thermal excitation. Therefore, thermodynamic processes and electromagnetic processes have exactly the same effect on the superconducting state. If the material is defective, a magnetic field or magnetic field lines can enter the defect. Superconducting electrons are excited by the magnetic field lines to generate a current surrounding the defect to produce a diamagnetic magnetic field. Any external magnetic field lines are interdependent with the surrounding current and the magnetic field generated by the surrounding current limits the changes of the external magnetic field lines which is the phenomenon of superconducting pinning. Complete diamagnetism is the inevitable result of having a zero-resistance orbit and electrons having energy to move in this orbit. Otherwise, how can the diamagnetism of electrons entering the superconducting state be activated when there is an external magnetic field? Because electrons need to move to create a magnetic field and to create complete diamagnetism. According to the principle of electromagnetism, a magnetic field has no effect on stationary electrons therefore stationary electrons cannot move in a magnetic field.
3. Josephson’s effect. This is the quantum tunneling effect between atoms. This also clearly proves that the participants in superconductor conduction are orbital electrons.
4. Mutation in heat capacity. Because superconducting electrons need to absorb heat when they transform into ordinary electrons, the object's thermal energy undergoes a downward mutation. After being transformed into free non-superconducting electrons, they participate in thermal motion and contribute to the heat capacity as normal free electrons. This is consistent with the usual energy gap theory explanation.

5. A good conductor of electricity is a non-superconductor. Meanwhile semiconductors, poor conductors, and even insulators may be superconductors. Why good conductors is not superconductors needs to be explained from the material structure. That an insulator can be a superconductor clearly proves that the free electrons that normally conduct electricity in a conductor are not the participants in the conduction of a superconductor. There is something else involved in the conduction of a superconductor and it is the orbital electron.
6. Applying pressure can lead to a transition from non-superconductor to superconductor, which clearly shows that the distance between atoms is critical. Proximity of atoms leads to orbital connectivity. Moreover, pressure affects the superconducting state more directly than temperature since if the material is not a superconductor, to lower the temperature cannot turn it into a superconductor. Pressurization can turn non-superconductors into superconductors, and pressurization can let the critical temperature higher. In addition, the object is heated with oxygen O or hydrogen H under high pressure, which allows O or H to penetrate between the atoms and ions and helps to link the superconducting orbit and help the object turn to a superconductor.

A. The effect of temperature：

The effect of temperature on a single superconducting electron is $\int_0^T \mathrm{C_{ev}}\, d\tau$, where $\mathrm{C_{ev}}$ is the specific heat of the superconducting electron. Although the superconducting electrons are in a superconducting orbit, the effect of the atomic nucleus on electrons is small so superconducting electrons can be approximately regarded as free electrons. The superconducting electrons are an electron Fermi sea in the superconducting ground state with the highest energy $\mathrm{k}T_c$. At low temperatures, it can be deduced that $\mathrm{C_{ev}} = \frac{27\mathrm{k}^2}{4}\frac{\mathrm{T}}{\mathrm{E_f^0}} = \beta\mathrm{T}$, where $\beta = \frac{27\mathrm{k}^2}{4\mathrm{E_f^0}}$, $\mathrm{E_f^0}$ is the highest energy of the Fermi electron sea, here $\mathrm{E_f^0} = \mathrm{kT_c}$, $\beta = \frac{27\mathrm{k}}{4\mathrm{T_c}}$. At high temperature, $\mathrm{C_{ev}} = \frac{3}{2}\mathrm{k}$, k is Boltzmann's constant. $\beta = \frac{27\mathrm{k}}{4\mathrm{T_c}}$ is obtained under low temperature condition and superconducting electrons are regarded as free electrons. In fact, superconducting electrons are in atomic orbits, and their energy levels have the highest energy limit. Although they are electrons which can globally move, they are not completely free electrons and are subject to orbital constraints. If the energy gap is large, it is like being in a deeper quantum potential well. The electrons in the well are similar to heavy electrons with greater mass, and the increase in mass is related to the atomic structure, energy gap and crystal lattice. Experimental data shows that heavy electron masses can vary by several orders of magnitude. This directly affects the specific heat of electrons and thus the critical temperature of superconductors. Under the same energy gap, the heavier the electron mass, the lower the critical temperature.

B. Consider the influence of the magnetic field again: an external magnetic field affects electrons with moving energy in orbit, which is different from conventional non-quantum phenomena. Usually moving electrons are affected by an external magnetic field, and the electrons become accelerated and radiate energy. After radiating energy, the electrons that have lost energy become stationary. The external magnetic field has no effect on stationary electrons. The action of the external magnetic field causes the moving electrons to lose energy and finally stop electrons moving. But it is completely different in the quantum world. Due to the quantum effect of the atomic nucleus, electrons outside the nucleus always move at a certain energy level. When an external magnetic field acts on the electron, although the magnetic force is a tangential force, it can increase the centrifugal acceleration of the electron, due to quantum effects, electrons always have speed. The tangential force of the magnetic field makes the electrons tend to break away from the nucleus. The external magnetic field causes the electron energy to increase. This is the energy increase caused by diamagnetism. The energy level of the electron is raised, and if the energy increase is greater than the excitation energy, thereby the electron enters a discontinuous orbit and the electron loses the superconducting state.

Superconducting electrons are in the superconducting ground state and are locally affected by the Coulomb force of the crystal lattice. When an external magnetic field is applied, the electron will receive additional force to produce diamagnetism, and the electron will gain extra energy. The maximum energy is $E_b = \frac{1}{2} e v_1 r_0 B$. If this energy is equal to the energy gap, that is, $E_b = \varepsilon$, the electron will be raised to the superconducting excited state, and the excited state deviates from the ground state position in the lattice. If the excited state is not globally continuous, the superconducting state will be destroyed, so we have $B_c = \frac{2\varepsilon}{e v_1 r_0}$.

In the presence of magnetic field B and temperature T, the total energy of superconducting electrons is：

$E = E_b + E_v + E_0$

The energy addition is

$\Delta E = E - E_0 = E_b + E_v$

When superconducting electrons are excited to an superconducting excited state, superconductivity disappears. Assume that the energy of the superconducting excited state is E_1. Once the superconducting electron obtains energy that exceeds the energy of the excited state, the superconducting electron jumps to the excited state and the superconducting state is destroyed, then the superconducting disappears. We have

When $\Delta E = \varepsilon = E_1 - E_0$, the superconducting state disappears, where $\varepsilon = E_1 - E_0$ is the difference from the superconducting ground state to the superconducting excited energy level, E_0 is the superconducting ground state, and E_1 is the superconducting excited state.
We have,

$$\mathbf{E_b + E_v = E_1 - E_0 = \varepsilon}$$

Critical magnetic field $\mathbf{B_c}$ is solution of equation $\mathbf{(E_b + E_v - \varepsilon)|_{T=0} = 0}$

$E_b = \varepsilon$

we get,

$$\mathbf{B_c = \frac{2\varepsilon}{e v_1 r_0}}。$$

Fundamentally, the greater the energy level difference from the superconducting ground state to the excited state, the greater $\mathbf{B_c}$.

Critical temperature T_c is solution of equation $(E_b + E_v - \varepsilon)|_{B=0} = 0$

$E_v = \varepsilon$

We can get T_c.

Fundamentally, the greater the energy level difference from the superconducting ground state to the excited state, the greater T_c; the smaller the specific heat of superconducting electrons, the greater T_c.

When the temperature is close to T_c, the thermal energy of superconducting electrons is more complicated. Superconducting electrons are free electrons in the superconducting ground state. When it is close to T_c, some superconducting electrons absorb thermal energy and transform into normal free electrons in the excited state to participate in thermal motion. At this process, thermal energy is absorbed by these electrons and the temperature of the object and the heat capacity will go down suddenly. Some electrons will become non-superconducting free electrons, which changes the relation of between the heat capacity and temperature. This is the electron heat capacity of the overall superconductor. For individual superconducting electrons, the assumption is that superconducting electrons are free electrons in the ground state and under the assumption we can calculate the specific heat of superconducting electrons when the temperature rises close to T_c. Only the superconducting electrons on the surface of the Fermi sea are activated by thermal energy, and the highest Fermi level is kT_c. The average specific heat of its superconducting electrons is，

Situation of T_c at low temperature： $C_{ev} = \frac{27k^2}{4}\frac{T}{E_f^0} = \frac{27k}{4}\frac{T}{T_c} = \beta T$， $\beta = \frac{27k}{4T_c}$， we have

$E_v = \varepsilon$

$E_v = \int_0^{T_c} C_{ev} d\tau = \frac{\beta {T_c}^2}{2} = \varepsilon$， ${T_c}^2 = \frac{8\varepsilon}{27k} T_c$， $T_c = \frac{8\varepsilon}{27k}$

$T_c = T = \sqrt{\frac{2\varepsilon}{\beta}} = \sqrt{\frac{8\varepsilon T_c}{27k}}$， $T_c = \frac{8\varepsilon}{27k}$

Due to orbital constraints, the movement of electrons is hindered, similar to heavy electrons. $T_c = \gamma\varepsilon$, $\gamma \leq 8/27k$, and γ is related to the critical temperature T_c and material structure. So γ is not a constant.

Situation T_c at high temperature: $C_{ev} = \frac{3}{2}k$, $E_v = \frac{3}{2}kT = \varepsilon$, $T_c = \frac{2\varepsilon}{3k}$.

T_c is directly and positively related to the energy level difference between the superconducting ground state and the superconducting excited state. But there is no strict simple mathematical equation between T_c and ε. γ in $T_c = \gamma\varepsilon$ is related to critical temperature T_c and material structure.

Taking into account the joint effects of temperature and external magnetic field,

$E_b + E_v = \frac{1}{2}ev_1r_0B + E_v = \varepsilon$

and $E_v = \int_0^T C_{ev}d\tau$, we have

$\frac{1}{2}ev_1r_0B = \varepsilon - \int_0^T C_{ev}\, d\tau$

$$\frac{B}{B_c} = 1 - \frac{\int_0^T C_{ev}\, d\tau}{\varepsilon} \qquad (2)$$

This is the general relationship between temperature and external magnetic field of superconducting state.

If T_c is t low temperature, then $C_{ev} = \beta T$, $E_v = \int_0^T C_{ev}d\tau = \frac{\beta T^2}{2}$, so we have

$\frac{B}{B_c} = 1 - \frac{\int_0^T C_{ev}\, d\tau}{\varepsilon} = 1 - \frac{\beta T^2}{2\varepsilon} = 1 - \frac{27kT^2}{8T_c\varepsilon} = 1 - (\frac{T}{T_c})^2$, where $T_c = \sqrt{\frac{\mathbf{2\varepsilon}}{\beta}} = \frac{8\varepsilon}{27k}$, $B_c = \frac{2\varepsilon}{ev_1r_0}$, $\beta = \frac{27k}{4T_c}$

$T_c = \sqrt{\frac{\mathbf{2\varepsilon}}{\beta}} = \sqrt{\frac{4ev_1r_0B_cT_c}{27k}}$

$$T_c = \frac{4ev_1r_0B_c}{27k} \qquad (3)$$

There is a deviation from the actual data because this formula is based on the assumption that superconducting electrons are free electrons. The actual electrons react with heat more slowly due to the attraction of the atomic nucleus, which is similar to the increase in the mass of the electron. At the same energy level difference ε, the critical magnetic field remains unchanged but the critical temperature becomes lower. Even though this formula at least explains the synchronization correlation between T_c and B_c.

$$\mathbf{\frac{B}{B_c} + (\frac{T}{T_c})^2 \leq 1}$$

The relationship between the B and the T is quadratic parabolic equation which is consistent with the usually given empirical relationship under low temperature conditions.

If T_c is at high temperature, then $B_c = \frac{2\varepsilon}{ev_1r_0}$, $T_c = \frac{2\varepsilon}{3k}$, $T_c = \frac{ev_1r_0B_c}{3k}$, and we have

$$\mathbf{\frac{B}{B_c} + \frac{T}{T_c} \leq 1}$$

B and T are linear relationships.

In general case,

$$\mathbf{\frac{B}{B_c} + (\frac{T}{T_c})^{\varphi} \leq 1}$$

Where $1 \leq \varphi \leq 2$, and φ is related to the critical temperature of superconducting objects. When the critical temperature is low, $\varphi = 2$, and when the critical temperature is high, $\varphi = 1$. Therefore, $\frac{\mathbf{B}}{\mathbf{B_c}} = \mathbf{1} - (\frac{\mathbf{T}}{\mathbf{T_c}})^{\mathbf{2}}$ is only true under low temperature conditions, but not for all superconductors at any temperature conditions.

Discuss the mutation in heat capacity of superconducting electrons

The contribution of superconducting electrons to the heat capacity is similar to a two-level system which has ground state energy and excitation energy. It is similar to a potential well quantum system with a well depth of ε, and the highest energy is kT_c. In the two-level system, due to the number of electrons participating of heat increases as an exponential function, and the specific heat is also in the form of an exponential function $e^{-\frac{\varepsilon}{kT}}$. When reaching the critical temperature, because the superconducting electrons absorb energy and transform into normal electrons, the specific heat drops sharply at this moment, and the electrons will become normal free electrons. At low temperature the specific heat will be $\frac{k^2}{E_f^0}T$ form. The heat capacity of a single superconducting electron is different from the overall heat capacity. Although it is in a superconducting orbit, the orbital constraints are weak, similar to free electrons in potential quantum well. This is a Fermi sea that is in the superconducting ground state with the highest energy of kT_c. The average specific heat of electrons is $\frac{27k}{4T_c}T$ form under low temperature conditions, which is the average specific heat of all superconducting electrons. This is different from the fact that the heat capacity of the overall superconducting electrons is an exponential function.

Key points and conclusions:

1. Whether a material is a superconducting material depends on whether there are global connected atomic orbits. The global connected atomic orbits are related to the atomic structure and lattice structure of the object whether the ground state diameter of the substance atoms, or the first/second excited state diameter, is close to the lattice distance or near enough. It can be achieved by replacing atoms with large ground state radius, or fill other atoms. It also can be achieved by compressing and shortening the lattice distance.
2. Raising the critical temperature depends on the energy difference between the atomic ground state and excited state which can help raising energy difference between the superconducting ground state and superconducting excited state, as well as the heat capacity of superconducting electrons. The greater the energy difference between the superconducting ground state and superconducting excited state, the higher the critical temperature; the lower the heat capacity of superconducting electrons, the higher the critical temperature. Replacing atoms with a small ground state radius by atoms with a large ground state radius can promote the close proximity and overlap of atomic orbits, thereby increasing the critical temperature. Moreover, if the excited states of atoms are connected to form a superconducting ground state, and the electrons enter the atomic ground state after the temperature is lowered, the ground state may not be a superconducting state. The superconducting temperature will be within a certain range, and objects above or below this range will lose their superconducting. There may also be

another situation where the atomic excited state of an object is a superconducting energy level, which is a global orbit, but the normal electron energy level cannot reach this energy level orbit. When the temperature increases, or the external magnetic field is strong enough to excite electrons to this energy level orbit, energy level, it will transform into a superconductor, just like lowering the temperature to induce a superconducting state. At this case, it is ultra-high temperature superconducting, but it is difficult to maintain the superconducting state because the energy level difference may be too small and ultra-high temperatures can also change substances from solid to liquid or gas. We can try to find this type of superconductor from superconductors which are superconducting material when low pressure is applied.

3. Filling in other atoms can also shorten the distance of the crystal lattice and change the energy level structure. Hydrogen atoms are important filler candidates due to their small size and large energy level difference from ground state to excited state. There are also other elements with high excitation energy. Preparing superconductors in a high-pressure hydrogen environment is also a good way. It only needs to embed high excitation energy, such as hydrogen atoms, on the surface of the object.

Conditions of superconducting materials

Global connected orbits between lattices are a necessary condition for superconductivity, and the superconducting ground state radius must be close to the lattice distance. The purpose can be achieved through adding small elements to fill the distance gap between atoms and pressurization. The close proximity and overlap of the superconducting ground state radius and the lattice distance can also increase the energy level difference, because more atomic energy levels participate in the superconducting ground state will cause the critical temperature to also increase. Critical temperature is the trigger for superconducting materials. Therefore, pressure is more fundamental than temperature, because pressure brings the superconducting ground state radius closer to the lattice distance, which can transform non-superconductors into superconductors.

The critical temperature is positively related to the energy level difference from the ground excited state to the excited state. Therefore, hydrogen atoms are the best choice, but hydrogen atoms are usually gases and must be compressed into a liquid or solid state so that their lattice structure is close to atomic orbits. Because the orbital radius of hydrogen atoms is too short, it is very difficult to transform it into a superconducting material.

Verification

Element H： radius from 32pm to 79pm， lattice a:470pm， b:470pm， c:340pm. Atomic radius is much smaller than the crystal lattice. Although its first excited state difference is very high: 10.2 ev. It is difficult to turn H into superconducting substances， but it can be a superconducting additive。

The first superconducting substance discovered: Hg.

Hg: lattice: a: 300pm, b: 300pm, c: 300pm. covalent radius: 149pm, very close.

Nb and Tc.

Nb: lattice: a: 330pm, b: 330pm, c: 330pm. orbit radius: 158pm, very close.

Tc: lattice: a: 273pm, b: 273pm, c: 438pm. orbit radius: 139pm, very close.

Why good conductors Cu, Au or Ag are not superconductors?

Cu: lattice: a: 361pm, b: 361pm, c: 361pm. maximum radius: 157pm, 40pm difference.

Ag: lattice: a: 408pm, b: 408pm, c: 408pm. maximum radius: 175pm, 50pm difference.

Au: lattice: a: 407pm, b: 407pm, c: 407pm. maximum radius: 179pm, 40pm difference.

The compound of these elements with other elements which even are not superconducting materials either is a superconductor. For example, copper is the main component of high-temperature superconductors, which means that there is nothing special about these elements themselves that prevents them from being superconductors and they are superconductors if they are in right condition. It's likely that the way the elements are combined to be lattice prevents them from becoming superconductors.

Why Na, K or Mg are not superconductors?

Na: lattice: a: 429pm, b: 429pm, c: 429pm. maximum radius: 171pm，80pm difference.

K: lattice: a: 532pm, b: 532pm, c: 532pm. orbit radius: 216pm，80pm difference.

Mg: lattice: a: 320pm, b: 320pm, c: 521pm. orbit radius: 128pm，80pm difference.

Pay special attention to atoms with large thermodynamic changes: lead, aluminum, tin, etc. Although their lattice distance is large, under low temperature conditions, due to their great thermal expansion and contraction characteristics, the lattice distance will shrink at low temperatures, which can produce global Orbits, thus they can be superconducting materials.

Calculation of the critical temperature of several elements by $\mathrm{T_c}=\frac{8\varepsilon}{27\mathrm{k}}$. Energy gap data source is from[3]：

Element	Energy gap(10^{-4} eV)	Critical temperature(k)	Calculated critical temperature(k)
Al:	3.4	1.175	1.169
V:	16	5.3	5.5
Zn:	2.4	0.85	0.82
Ga:	3.3	1.1	1.1347
Nb:	30.5	9.26	10.487

Mo:	2.7	0.92	0.9283
Cd:	1.5	0.515	0.5157
In:	10.5	3.146	3.61
Sn:	11.5	3.7	3.954
Ta:	14	4.48	4.813
Hg:	16.5	4.15	5.673
Tl:	7.35	2.39	2.527
Pd:	27.3	7.19	9.387

The calculated critical temperature agrees well with the measured critical temperature. But the larger the energy gap, the larger the error. Because the larger the energy gap means the more nucleus affect on electrons, which is inconsistent with the prerequisite condition of the formula $T_c = \frac{8\varepsilon}{27k}$: superconducting electrons are free electrons. Because superconducting electrons are not complete free electrons then errors arise. If the potential well is shallower(meaning ε is less) the electrons are more free. It can also be seen that heavy fermions reduce the critical temperature. Although large energy gap can increase the critical temperature, but its actual value is lower than the calculated value.

Summarize

Whether a substance is a superconductor depends on whether it has a global electron energy level orbit.

The Zero-resistance conduction and complete diamagnetism of superconducting state are two aspects of the existence of superconducting global superconducting orbit: electrons moving in orbit have no energy loss, and orbiting electrons must have diamagnetic effect against external magnetic field.

The critical temperature depends on: 1. The energy level difference between the superconducting ground state and the superconducting excited state. 2. And the overlap between the atomic spacing and the position of superconducting ground state because the more the atomic spacing coincides with the position of superconducting ground state, the more difficult it is to destroy the superconducting state. 3. The heat capacity of electrons in the superconducting state.

The greater the energy level difference, the higher the critical temperature; the higher the overlap between the atomic spacing and the superconducting ground state, the higher the critical temperature, the greater the heat capacity of electrons in the superconducting state, the lower the critical temperature.

There are superconductors with two critical temperatures. Only if the temperature is between the two critical temperatures, the object is in a superconducting state. This is because the superconducting ground state is an atomic excited state.

The critical magnetic field depends on many factors such as the energy level difference between the superconducting ground state and the superconducting excited state. The greater the energy level difference, the higher the critical magnetic field.

For superconducting materials the temperature is related to the magnetic field in the form of $\frac{\mathbf{B}}{\mathbf{B_c}} + (\frac{\mathbf{T}}{\mathbf{T_c}})^{\boldsymbol{\varphi}} \leq \mathbf{1}$, where $1 \leq \phi \leq 2$. Critical temperature is related to critical magnetic field.

Methods to increase the critical temperature include: reducing the distance between lattice is the primary means: It can be achieved by adding atoms among the lattice and hydrogen atom is a excellent filler; It can also be achieved by compress to shorten the lattice distance. For superconductors, looking for substances with a large energy difference from the ground state to the excited state is another important means to increase the critical temperature.

Discuss

C_{60} is a relatively special type of superconductor. It has special electrical and thermal conductivity properties. It is similar to a large molecule. It is doped with other atoms to close the atomic distance and form a global orbit. It can become a superconductor. The basic principle should be the same, but because of its Special thermal conductivity, its Fermi sea is different from ordinary substances and the relationship between critical temperature, critical magnetic field and energy gap is unusual, which may need to be considered separately.

Reference

[1] *Kamerlingh Onnes. Further experiments with liquid helium. D. On the change of electric resistance of pure metals at very low temperatures, etc. V. The disappearance of the resistance of mercury.. Comm. Phys. Lab. Univ. Leiden. 1911, (122b).*

[2] Walther Meißner and R. Ochsenfeld, Naturwissenschaften V21, p. 787 (1933).

[3] Kittel, Charles. Introduction to Solid State Physics, 5th edition. New York: John Wiley & Sons, Inc, 1976