Electron Tunnel

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The concept of electron tunnels is the key to understanding superconductivity and expediting the process of finding or engineering room-temperature superconductors. An **electron tunnel** refers to the network of electron paths between molecules in a conductor where electrons can flow along the paths at the same energy level, resulting in currents. An electron, with an energy level below the electron tunnel, remains confined within its orbital[1] inside the individual molecule and cannot produce any current. To create currents in a conductor, electrons must be at a sufficient energy level to move through the electron tunnel.[2] So, the space in a conductor is divided into two types of regions: a network of electron tunnels and isolated cells around individual molecules, much like the spaces between cement and pebbles in a piece of concrete. An electron tunnel does not always appear in all materials. It is necessary for conductors, but absent in insulators. A superconductor[3] is a special conductor with valence orbitals intersecting the electron tunnel. Therefore, the valence electrons move naturally in the electron tunnel without needing energy to elevate them to the electron tunnel. It is essential to note that the term "conduction band" refers to a distinct concept defined in band theory.[4]

The term electron tunnel was introduced in the "Unified Theory of Low and High-Temperature Superconductivity."[2] It establishes a unified theoretical framework for low- and high-temperature superconductivity[5] and provides a cohesive approach to understanding the differences among insulators, conductors, and superconductors. Insulating, conducting, and superconducting can be different electrical states of the same matter. Transitions between these states are typically associated with the electron tunnel's response to changes in pressure and temperature conditions. Furthermore, the concept of the electron tunnel provides a comprehensive explanation for various phenomena observed in superconductivity. It offers practical guidelines for the search and development of superconductors operating under standard Earth conditions.

Attraction Coefficient

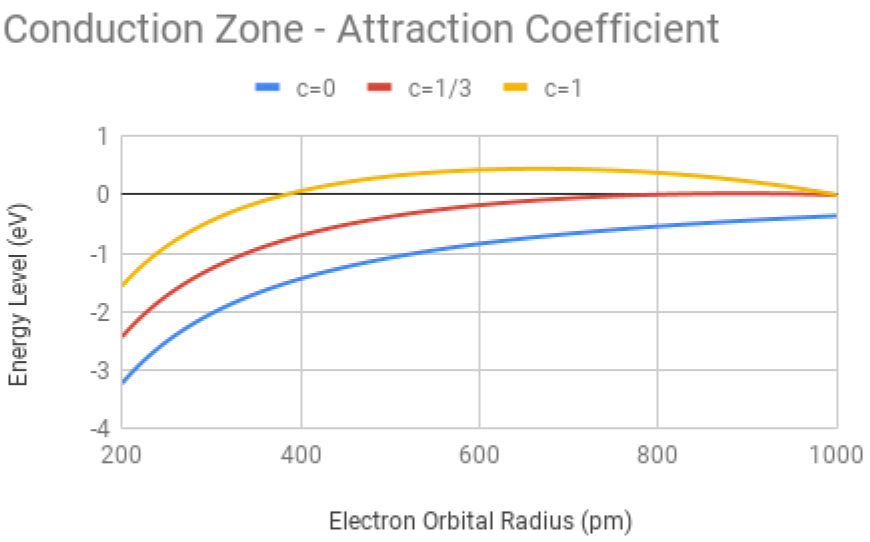
Outer shells of the electron cloud of atoms in a molecule are typically distributed unevenly, resulting in various intermolecular forces.[6] Intermolecular attractions, or bonds, hold molecules at a close distance, which is crucial to developing electron tunnels, enabling electrons to flow between molecules. It is important to note that molecular bonds, such as covalent bonds,[7] allow electrons to move between atoms within individual molecules but do not facilitate electron movement between different molecules, necessary for the current generation.

To learn the influence of bonding intensity on electron tunnels and to identify the boundary between the electron tunnel and molecule cells in a conductor, the concept of attraction coefficient is introduced, denoted by the symbol c.[2] This coefficient models the intensity of the attraction of an electron by an adjacent molecule, such as that due to a metallic bond.[8] Assume that an electron is attracted by its nucleus with an equivalent charge Q, taking into account other electrons in the same molecule. The attraction to the electron by an adjacent molecule in the crystal lattice can be modeled as if it were from a charge of cQ. The value of c is typically between 0 and 1. An adjacent molecule with an electron-hole has the equivalent influence on the electron from the original molecule, i.e., $c = 1$. When $c = 0$, it indicates the adjacent molecule does not influence the electron. Hence, the force exerted on the electron by both molecules can be determined, even when considering all the molecules in the crystal. Consequently, the energy level of the electron and the potential fields between molecules can be calculated at any given location within the lattice structure.

For instance, the Coulomb force[9] exerted on an electron on the centerline between two molecules can be determined by

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

where K represents the Coulomb constant,[10] e is the charge of the electron, r is the orbital radius of the electron, and R is the half distance between the centers of the two molecules, representing the distance to the border between the molecules. Different values of c model various attraction intensities due to different molecular bonds. This model may be extended to include the influences of all the molecules in the crystal lattice of a conductor. However, the effects of other molecules decrease rapidly with increasing distance from the original molecules, making their contributions less significant in the overall interaction.



The relationship between electron tunnel width and attraction coefficient is illustrated using a model in which a molecule is located 2000 pm away from an adjacent molecule with a bonding strength represented by an attraction coefficient c. Each curve represents the energy levels of an electron as a function of the electron orbital radius for a specific attraction coefficient. The x-axis starts from the molecule's center and extends towards the adjacent molecule. The figure displays only a section of an electron energy level from 200 pm away from the molecule center to the border with the adjacent molecule. The electron energy level increases at orbitals away from the molecule's center towards the border. When c = 1, the energy level increases from negative values, turning positive from a radius of 382 pm, as illustrated by the yellow curve. A positive energy level indicates the electron is no longer confined by its nucleus and can move between molecules. Thus, the region of the positive energy level represents the electron tunnel. Note that with c = 1, the curve simulates the attraction from an adjacent molecule with an electron hole, creating the widest electron tunnel. When c = ⅓, the energy level turns positive from a radius of 785 pm, resulting in a smaller electron tunnel, as shown by the red curve. When c = 0, the energy level remains entirely negative, indicating no electron tunnel, as illustrated by the blue curve.

Using this model, the energy level of an electron is calculated along the centerline between two single-atom molecules with c = 1.[2] It increases from a negative value near the nucleus of its atom, reaches zero at an orbital radius or a distance from its nucleus that is 0.382 of the half-nucleus distance between the two atoms, and becomes positive further toward the border between the atoms. The positive energy level indicates the electron is no longer confined by its nucleus and can move between different molecules. Therefore, the region with positive energy defines the electron tunnel. The zero energy point identifies the intersection of the centerline with the boundary between the molecule cell and the electron tunnel.

When c = ⅓, the energy level becomes positive at an orbital radius that is 0.785 of the distance to the border, resulting in a smaller or narrower electron tunnel. With c = 0, the energy level remains entirely negative, indicating the absence of an electron tunnel, which corresponds to the insulating state of matter. In general, the width of the electron tunnel decreases with decreasing c and disappears at a value of around 0.225. This demonstrates the relationship between the attraction coefficient, representing bonding intensity between molecules, and the extent of the electron tunnel, relating to the electrical state of matter.

The Nature of Resistivity and Superconductivity

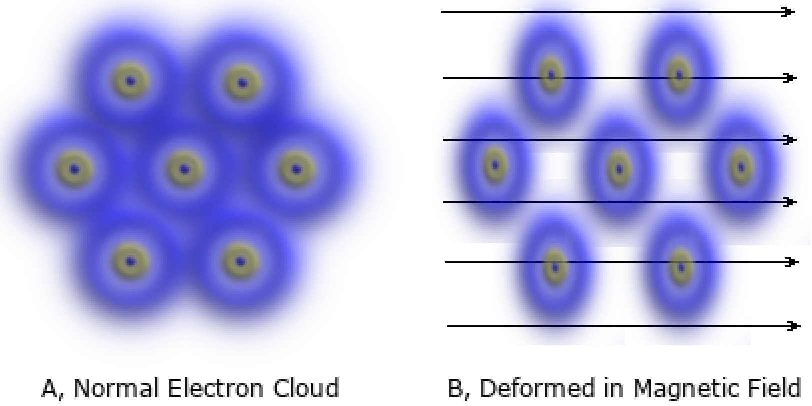
Due to Coulomb's force, an electron, carrying a negative charge, is always influenced by nearby nuclei and electrons.[10] Its movement is governed by the fields, not randomly within a conductor. Each electron travels in an orbital path corresponding to its energy level. At low energy levels, an electron is limited to its atomic orbitals.[1] It may move between atoms within the same molecule, such as shared electrons in a covalent bond.[7] However, these movements do not produce electrical currents. As a result, low-energy electrons are confined in their molecular cells before being excited into high levels by external energy.

At higher energy levels, an electron can travel between molecules along the electron tunnel, generating a current in a conductor.[2] The electron tunnel can be perceived somewhat as a shared orbital at a high energy level among multiple molecules and serves as an isoenergy pathway for electrons to flow between molecules in a conductor. It is important to note that an electron tunnel is not a free space between molecules where electrons can move randomly. An electron tunnel is filled with electrical fields created by charges of surrounding molecules, where only electrons with sufficient energy can travel in it. Instead of random movement, the flow of electrons is completely governed by the fields.

To create currents in a conductor, valence electrons must be elevated to the electron tunnel. The energy required to raise electrons is the cause of electrical resistance.[11] The excited electrons tend to retreat to lower orbitals where there are electron holes, dissipating their energy as heat in the form of photons.[12] Therefore, the resistivity of a conductor relates directly to the energy gap between the electron tunnel and valence orbitals, and specifically, a smaller gap corresponds to lower resistivity.[2] In the case of a superconductor, some valence orbitals intersect the electron tunnel, effectively eliminating the energy gap. Hence, the valence electrons reside naturally in the electron tunnel without the need to lift to the zone to create currents, resulting in zero resistance.

Explaining the Properties of Superconductivity

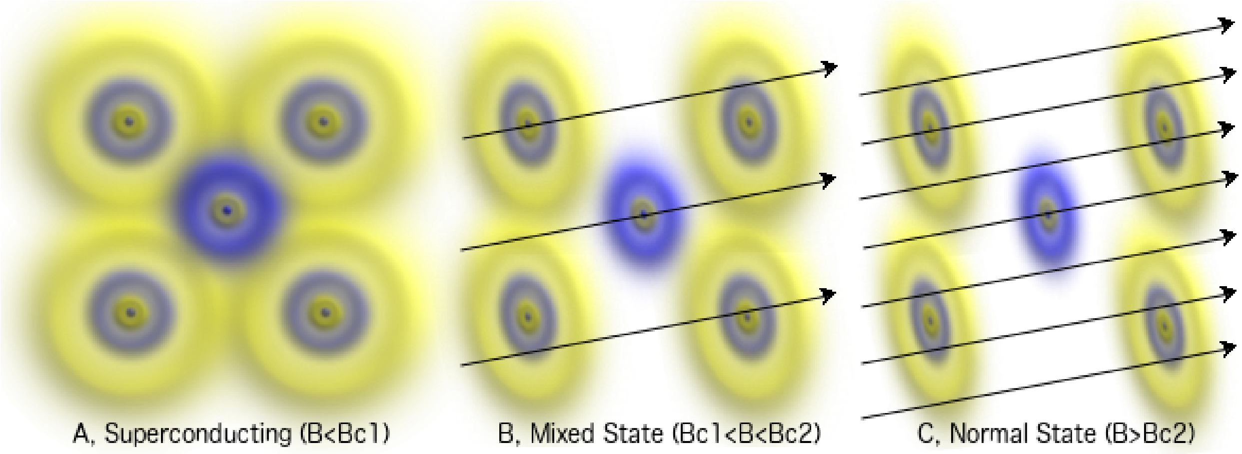
In an external magnetic field, moving electrons in the electron tunnel of a superconductor are deflected by the Lorentz force.[13] Consequently, the electrons circulate in a direction to generate a magnetic field that compensates for the external field inside the superconductor and superimposes the field outside,[2] resulting in the Meissner effect.[14] The number of moving electrons in the electron tunnel limits the maximum current density in the superconductor, known as the critical current density of the superconductor.[15] As the external magnetic field increases to an intensity where the movement of all electrons in the electron tunnel cannot completely cancel the applied field, the remaining external field deflects the orbital electron movement, primarily the valence electrons. The electron clouds are compressed along the direction of the external field. To a certain extent, the valence electrons are pulled below the electron tunnel, destroying superconductivity.[2] The maximum survival field is known as the critical field of the superconductor.[16] This explains the correlation between the critical magnetic field and the critical current density of a superconductor.



The destruction of superconductivity in a magnetic field can be explained by the concept of electron tunnels. (A) In the absence of or in a weak external magnetic field, the applied field can be completely canceled by the internal field due to the Meissner effect, as if there is no external field present. The electron cloud of valence electrons extends normally in a superconductor. Superconductivity may withstand a magnetic field up to a critical level. (B) However, above the critical intensity, an external field cannot be completely canceled due to the limit of the critical current density. Orbital electrons are deflected by the Lorentz force in the remaining field and divert their orbital plane in the direction perpendicular to the field. This action compresses the shape of the electron clouds like squashed lanterns, perpendicular to the applied field. The deformation of the orbitals pulls the valence electrons below the electron tunnels, leading to the destruction of superconductivity.

A type-II superconductor[17] is typically composed of alloys or compounds. The bonding strengths and widths of the electron tunnels vary between different molecules. As a result, its superconductivity in different regions survives in different external magnetic fields. The two critical fields of a type-II superconductor are the minimum and maximum survival fields. Due to the asymmetric crystal structure, the superconductivity of the same region may be destroyed at different field intensities from different directions. Thus, the critical fields of a type-II superconductor are sensitive to and vary in the direction of the applied fields. In the mixed state, the regions where superconductivity is destroyed become normal conductors and form vortices,[18] allowing the external magnetic fields to pass through. As the applied field increases, more and more regions with higher critical fields are destroyed, increasing the density of vortices.

The flux quantum is the minimum value of magnetic flux, which is created by the movement of a single electron.[19] It can be determined by the Schrödinger equation to be h/2e, where h represents the Planck constant and e is the charge of an electron. This prediction can be verified using a superconductor in a donut shape. For an electron to move between molecules, it must start with an electron orbital transition, which also results in an electron-hole pair. Thus, the flow of an electron must be accompanied by a drift of the electron-hole, therefore creating two flows of charges simultaneously. The minimum flux in a donut-shaped superconductor is a result of the two flows in opposite directions around the donut, equivalent to two electrons moving in the same direction. This predicts the minimum flux in a superconductor to be twice the flux quantum, which has been confirmed in experiments by B. S. Deaver and W. M. Fairbank,[20] and independently by R. Doll and M. Näbauer.[21]



The properties of type-II superconductors can be explained by the responses of electron tunnels to external magnetic fields applied from different directions. (A) A type-II superconductor is typically composed of alloys or compounds. In a magnetic field below the minimum critical intensity, electron tunnels between all molecules are intact, and superconductivity is maintained entirely. (B) In a field between the minimum and maximum intensities, some valence electrons are pulled out of the electron tunnels by the Lorentz force, such as the valence electrons of the small molecule at the center, resulting in vortices or superconducting holes in the mixed state around small molecules. (C) In a field above the maximum critical intensity, the entire superconductivity is destroyed as all the valence electrons are pulled out of the electron tunnels. Additionally, note that the deformation of the electron cloud is affected by the direction of the applied field, which is why the critical fields of a type-II superconductor may vary depending on the direction of the external field.

Electrical Resistance States of Matter

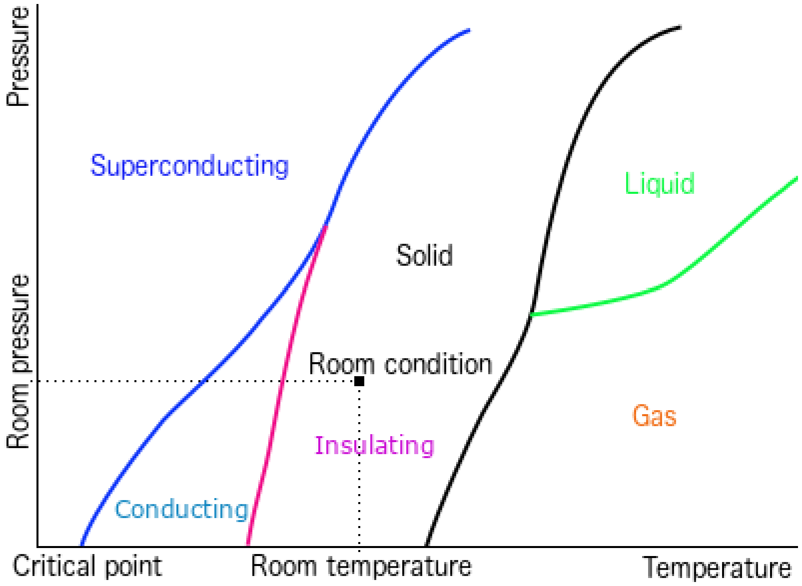
Solid and fluid are different shearing resistance states of matter at various pressures and temperatures.[22] Similarly, a substance can also display different electrical resistance states (insulating, conducting, and superconducting) and transition from one state to another at different pressures and temperatures.[2]

As pressure increases, while the distance between molecules is reduced, the resistivity of a conductor decreases with the reduction in the gap between the electron tunnel and valence orbitals. This explains the observations of negative correspondence between pressure and resistivity.[23-25] At certain high pressures, this gap can eventually be reduced to zero, eliminating electrical resistance and resulting in superconductivity. This is why more and more superconductors are obtained at high pressures, and some ceramics, expected insulators, transition to superconductors at high pressures.[26-29]

At low temperatures, electrons tend to retreat to lower orbitals, decreasing the repulsion between molecules. As a result, the surrounding pressure on Earth becomes more significant, reducing molecular distance and creating a compression effect equivalent to a pressure increase. This explains the positive correlation between temperature and resistivity in conductors, as well as why conventional superconductors are typically observed at low temperatures.[30-31]

Attractions, or bonds, develop at short distances between molecules. Some of them, such as compression bonds,[32] are induced primarily due to interaction between molecules at high pressures. Hence, the attraction coefficient typically increases with pressure, which also reinforces the negative relationship between pressure and resistivity.

In general, increasing pressure reduces the gap between the electron tunnel and the valence orbitals, therefore decreasing the resistivity of conductors.[2] Pressure increases the attraction coefficient, leading to wider electron tunnels and also reducing the resistivity of conductors. Thus, as pressure increases, an electron tunnel may develop in an insulator, which transitions the insulator into a conductor. As pressure increases further, the electron tunnel becomes wider and the gap between the electron tunnel and valence orbitals decreases, reducing the resistivity of the conductor. At even higher pressures, the gap can be completely closed, eliminating the resistance in the conductor and resulting in a superconductor. As mentioned earlier, the decrease in temperature at a constant surrounding pressure creates an equivalent compression effect, resulting in a positive correlation between temperature and resistivity. Therefore, pressure and temperature play crucial roles in determining the electrical states of matter.



An illustrative electrical resistance state diagram depicts superconducting, conducting, and insulating transition boundaries, besides the transition boundaries of conventional shearing resistance states. The transition boundary for superconductivity typically resides on the low-temperature and high-pressure side of room conditions, explaining why room-temperature superconductors are less common due to unfavorable conditions on Earth. An insulating transition boundary of a substance may intersect with the superconducting transition boundary when there is a direct transition from an insulator to a superconductor.

The critical point of a superconductor refers to the specific transition temperature observed at a particular pressure. For a conventional superconductor, this critical point is measured under normal Earth pressure. A superconductor may exhibit multiple critical temperatures at different pressures.[2] All these critical points collectively depict the superconducting transition boundary in a state diagram.

From a different perspective, the resistivity of a conductor can be conceptualized as a function of pressure and temperature. This relationship can be visualized as a surface, where each point on the surface represents the resistivity at a specific pressure and temperature. The superconductivity transition boundary is the curve where the surface intersects with the pressure-temperature plane at zero resistivity.

At the microscopic level, the conducting-superconducting transition boundary signifies the pressures and temperatures under which the electron tunnel starts to overlap with valence orbitals. The conducting-insulating transition boundary indicates the pressures and temperatures at which the width of the electron tunnel reduces to zero, which corresponds to an attraction coefficient of approximately 0.225 predicted in the model mentioned earlier.

Engineering Room-Temperature Superconductors

With the understanding of the microscopic nature of superconductivity, the pursuit of room-temperature superconductors is no longer a random endeavor but becomes a deliberate engineering task. While the electron tunnel theory predicts superconducting to be an ordinary state of matter,[2] the vast majority of substances exhibit superconductivity only under extremely high pressures and/or low temperatures. For practical applications, it is necessary to develop superconductors that can operate under normal conditions on Earth. Here are some guidelines based on the electron tunnel theory that should significantly narrow the search paths for room-temperature superconductors:

- The engineering task needs to leverage intermolecular attractions to overcome the repulsions. By arranging molecules to introduce attractions between certain molecules, these molecules can be compressed in close proximity, and it becomes possible to create expansive electron tunnels that overlap with valence orbitals.
- Electronegativity[33-34] plays a crucial role in the selection of elements for synthesizing superconductors. It is important to avoid elements with excessively high electronegativity, as they tend to tightly hold onto electrons, such as Cl in NaCl, hindering the flow of current between molecules. Conversely, elements with insufficient electronegativity are unable to establish the necessary intermolecular attractions needed to develop wider electron tunnels. To prevent certain atoms from excessively retaining electrons, it is advantageous to choose elements with a narrow range of electronegativities. By maintaining a close range of electronegativities among the selected elements, it becomes possible to strike a balance that promotes the formation of interconnected electron tunnels and facilitates optimal electron flow between different molecules.
- It is essential to steer clear of excessively complex, large compound molecules, as they can disrupt the connectivity of electron tunnels, similar to the situation observed in most insulators. A high-quality superconductor must have well-connected electron tunnels so that it allows the flow of currents in all directions. Overcomplex molecules likely introduce insulating regions, which may interrupt the electron tunnels.
- The molecular structure of compounds and alloys that incorporate a combination of large and small atoms gives rise to irregular intermolecular fields and forces, thereby increasing the likelihood of fostering intermolecular attractions and compressions between certain molecules.

Revision History

- 08/29/2023: Initial Post on Stanford Site
- 11/01/2025: Published on Zenodo
- 12/17/2025: Adding Links to Summaries of Related Articles

Links to Summaries of Related Articles

- https://cs.stanford.edu/people/zjl/abstract.html, PDF
- https://sites.google.com/view/zjl/abstracts, PDF
- https://xenon.stanford.edu/~zjl/abstract.html, PDF
- https://doi.org/10.5281/zenodo.17967154, PDF

Further Literature

- Misconceptions in Thermodynamics (PDF: DOI) (中文: DOI)
- The Mechanism Driving Crookes Radiometers (PDF: DOI) (中文: DOI)
- The Cause of Brownian Motion (PDF: DOI) (中文: DOI)
- Can Temperature Represent Average Kinetic Energy? (PDF: DOI) (中文: DOI)
- The Nature of Absolute Zero Temperature (PDF: DOI) (中文: DOI)
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- Is There a Sea of Free Electrons in Metals? (PDF: DOI) (中文: DOI)
- Electron Tunnel (PDF: DOI) (中文: DOI)
- Unified Theory of Low and High-Temperature Superconductivity (PDF: DOI) (中文: DOI)
- LK-99 Limitations and Significances (PDF: DOI) (中文: DOI)
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