LK-99 Limitations and Significances

Liu, Jerry Z.
ZJL@CS.Stanford.EDU

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LK-99 Mysteries

A research team from Korea University recently claimed to have synthesized a room-temperature superconductor, called LK-99, which reportedly exhibits superconductivity at 400 K (127 °C) under ambient pressure. This announcement sparked a global effort among scientists to replicate and verify the material's properties. While many groups have failed to reproduce the superconducting behavior, some have reported observing limited superconductivity-like features in small samples. These findings have led some researchers to suggest that the observed effects may stem from Cu_2S impurities rather than the intrinsic properties of LK-99 itself. Notably, LK-99 crystals synthesized at the Max Planck Institute did not demonstrate any superconductivity. This raises fundamental questions: Is LK-99 truly a superconductor? What explains the significant variation in experimental outcomes? Compounding the mystery, most reports of superconductivity involve only very small regions of the material, and no superconductivity has been observed in single LK-99 crystals. The Electron Tunnel Theory, as proposed in the Unified Theory of Low and High-Temperature Superconductivity, may offer insights into these puzzling phenomena.

The Challenges to BCS Theory

Superconductivity is typically explained in the BCS theory. However, it cannot account for high-temperature superconductors typically obtained under high pressures. BCS theory is implicitly based on the Drude model for electrical resistance, as depicted in Figure 1. In the Drude model, electrical resistance is assumed to be caused by collisions between free-flowing electrons and the crystal lattice in conductors. Each collision dissipates some of the electron's energy, resulting in electrical resistance.

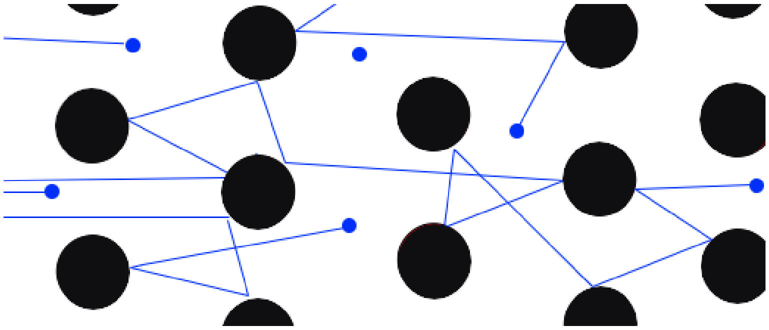


Figure 1. The Drude model for electrical resistance.

In BCS theory, an electron can attract nearby nuclei at low temperatures, creating a high-density region of positive charges. This positive region further attracts other electrons. Through this indirect attraction, electrons can pair up, known as a Cooper pair. Electrons flowing in pairs through molecules are more stable, reducing the chance of collisions, minimizing the resistivity, and resulting in zero resistance in superconductors. However, Cooper pairs will break apart due to particle vibration at temperatures over 40 K. So, superconductivity should not be observed at high temperatures based on BCS theory. However, more and more superconductors have been discovered at temperatures much higher than 40 K. Where is the problem?

If the Drude model were correct, one would expect high-density materials to be more resistive. As confining pressure increases, molecules are packed more densely in conductors, and the chances of collisions increase. Consequently, higher resistivity should be observed. But observations are just the opposite: resistivity is negatively related to pressure. As pressure becomes extremely high, zero resistivity is eventually observed in many materials, even at very high temperatures. So, it may be an incorrection assumption in the Drude model that the cause of electrical resistance is due to collisions. The failure of the BCS theory is a consequence of this incorrect assumption.

Electron Tunnel Theory

The principle of the electron tunnel theory is quite straightforward. Electrons are normally confined within the atoms of individual molecules and typically cannot move freely between molecules. The space between molecules is not a vacuum but is filled with electrical fields created by nuclei and electrons. An electron, with a negative charge, is influenced in these fields and is unlikely to move freely. To generate a current in a conductor, energy must be added to electrons to elevate them to higher energy orbitals between molecules. These higher-energy electrons can then move along the shared orbitals, traversing between molecules, resulting in currents, as illustrated in Figure 2. Hence, the interconnected orbital paths may be conceptualized as electron tunnels between molecules.

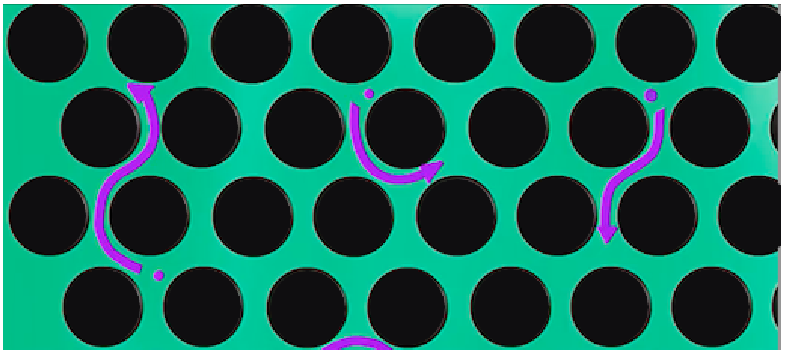


Figure 2. Electron tunnels between molecules.

Occasionally, a high-energy electron may drop off the electron tunnels and fall into an electron hole, releasing the energy it absorbed earlier, which causes electrical resistance. The heat produced in electrical devices is the energy released as electrons transition to lower orbitals and is not due to collisions as assumed in the Drude model.

Based on this principle, it can be predicted that resistivity in a conductor is positively related to the spacing between molecules. To generate a current across molecules with greater distances, as shown in Figure 3(A), more energy is required to raise electrons, and a larger amount of energy is dissipated when these electrons fall back into electron holes. As a result, the conductor exhibits higher resistivity. In superconductors, the molecular spacing is sufficiently small that certain valence orbitals extend into the electron tunnels, as illustrated in Figure 3(B). Consequently, valence electrons can enter the electron tunnels and flow across molecules without the need for lifting energy, therefore, free of resistance.

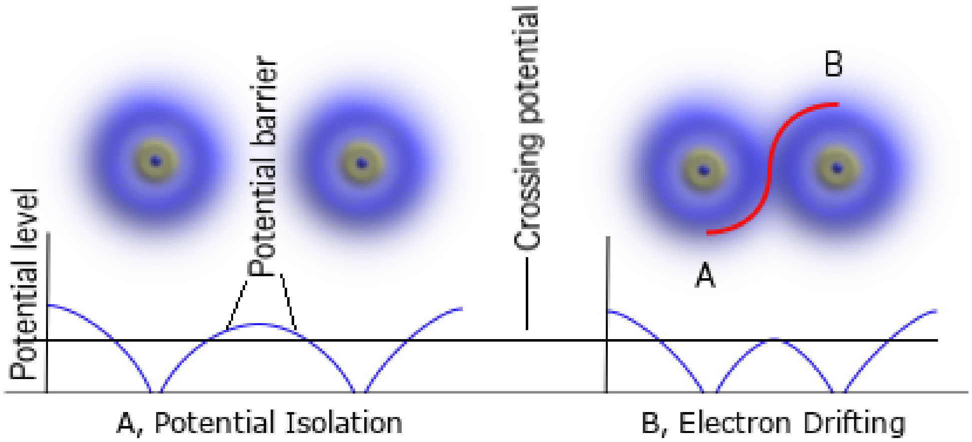


Figure 3. The spacing between molecules in conductors (A) vs. superconductors (B).

This clarifies why superconductivity can be achieved with high pressures, even at very high temperatures, as the spacing between molecules can be monotonically reduced under pressure. The same mechanism accounts for conventional superconductors observed at low temperatures. As the temperature drops, electrons retreat to lower orbitals, reducing the size of atoms/molecules and decreasing the repulsion between them. Consequently, the Earth's atmospheric pressure, which remains relatively consistent, becomes increasingly significant, compressing the molecules and diminishing the spacing between them, thereby replicating the compressing effect under high pressures, as depicted in Figure 4(A).

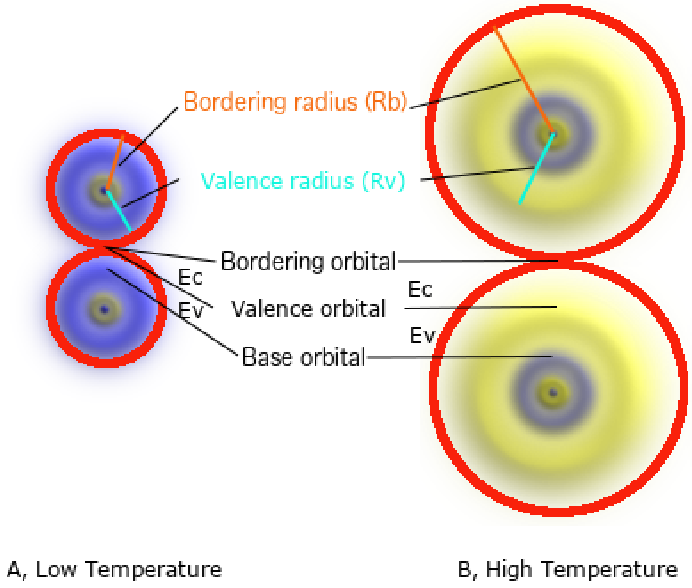


Figure 4. The valence orbitals at low temperatures (A) vs. high temperatures (B).

Conversely, when the temperature rises, electrons become more active and often excite to higher orbitals, as illustrated in Figure 4(B). The volume of atoms and molecules increases, which raises the repulsive force between molecules and pushes the molecules apart at greater distances. Under relatively constant atmospheric pressure, the repulsion between molecules dominates, causing the molecular distance to increase more rapidly than the expansion of valence orbitals. Consequently, the valence orbitals and electrons fall below the shared electron tunnels, resulting in the loss of superconductivity. As the temperature continues to rise, the molecular spacing will further increase, the volume of the conductor will expand, and the resistivity will also increase. Hence, the electron tunnel theory unifies the mechanisms of conductor resistivity and both low/high-temperature superconductivity.

In general, the resistivity of a conductor corresponds to the variations in molecular distance, a dynamic property determined primarily by ambient pressure and/or temperature. Superconductivity emerges as an inevitable outcome of this trend at elevated pressures, and potentially at low temperatures as well. In essence, with sufficient pressure, any material has the potential to transform into a superconductor. However, the standard pressure and temperature conditions on the Earth's surface are not favorable for the development of superconductivity in most substances. Contrastingly, superconductors might be common deep inside most large planets, including Earth. The currents flowing in these superconductors might be responsible for the origin of the planet's magnetic fields. The superconductor origin of the geomagnetic field is a different subject, and interested readers are encouraged to explore the referenced literature for more details.

Engineering of Room-Temperature Superconductors

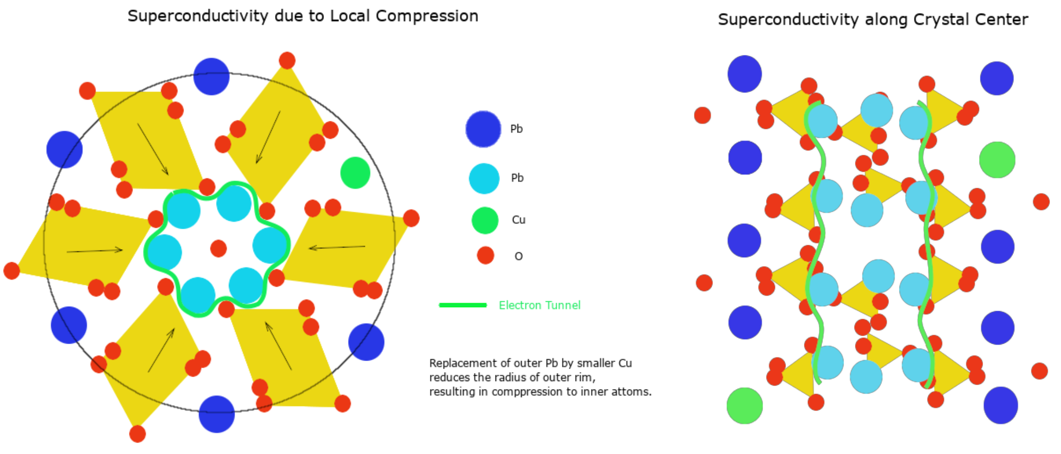
The elegance of the electron tunnel theory lies not only in its ability to explain the properties of conductivity and superconductivity in a single mechanism but, more importantly, in its provision of practical guidelines for synthesizing superconductors. By comprehending the microscopic essence of superconductivity, synthesizing room-temperature superconductors is no longer a random endeavor but becomes a deliberate engineering task. The ultimate strategy in synthesizing superconductors involves compressing the gaps between molecules. Outlined below are key principles that can significantly narrow down the search for room-temperature superconductors:

- The engineering approach should harness molecular attractions to counteract repulsions. By designing the molecule structures to foster attractive forces between specific atoms, it becomes feasible to bring together certain atoms nearby, enabling their valence orbitals to extend into the electron tunnels between them.
- Electronegativity plays a crucial role in the choice of elements for synthesizing superconductors. It is important to steer clear of elements with exceedingly high electronegativity, as they would strongly retain electrons. Opting for elements in a narrow range of electronegativities may be necessary to avoid unbalanced electronegativity.
- Excessively complex and large compounds have the potential to disrupt the continuity of electron tunnels. A connected electron tunnel should be at the same potential/energy level. In a crystal made of complex molecules, the field intensities between different regions are likely uneven, as in most insulators.
- The molecular structure of compounds or alloys that incorporate a combination of large and small atoms gives rise to uneven intermolecular tensions, thereby increasing the likelihood of fostering compressions between certain atoms and the development of superconductive paths between them.

LK-99 Limitations and Significances

Some LK-99 specimens have been observed to exhibit limited or partial superconductivity-like characteristics. The reduction in resistivity has been attributed by some researchers to the presence of impurities like Cu_2S in the samples. However, Cu_2S is a semiconductor with significantly higher resistivity than Cu, making it far-fetched to account for the observed diamagnetism. Certain individuals attribute the observed magnetic levitation to the weak ferromagnetic properties of Cu_2S. However, ferromagnetic objects typically have two opposing magnetic poles, and these poles can either attract or repel the north pole of a magnetic field. Therefore, when the external magnetic field reverses, the specimen should flip upside down. This phenomenon is easily observable. However, the diamagnetism demonstrated in the video from Huazhong University of Science and Technology did not exhibit this ferromagnetic characteristic. A more plausible explanation for these observed phenomena is due to the limitation of localized superconductivity, which is inherent to the structural constraints of LK-99 crystals. This is discussed in more detail below.

The LK-99 crystal resembles a cylinder-like hexagonal structure. Its outer framework is composed of Pb atoms and PO_4 structures, surrounding an inner cylinder consisting of Pb and O atoms, as shown in Figure 5. When a larger Pb atom is replaced by a smaller Cu atom in the outer shell, the Cu atom pulls in the neighboring atoms, reducing the radius of the outer shell and compressing the inner atoms, as illustrated in Figure 5(A). This compression brings the inner Pb and O atoms closer in proximity. Consequently, the valence orbitals and electrons associated with these inner Pb and O atoms extend into the electron tunnels between them. Ideally, this arrangement facilitates the superconductivity between the inner Pb and O atoms along the center portion of individual crystals, as depicted in Figure 5(B).



A, Top view of LK-99 crystal structure

B, Side view of LK-99 crystal structure

Figure 5. Top view (A) and side view (B) of the LK-99 crystal structure.

However, in LK-99, superconductivity is confined locally to a one-dimensional path along the interior of the crystal structure, which limits the freedom of current flow. Imagine each LK-99 crystal as a small piece of insulated wire, and an imperfect LK-99 specimen may be conceptualized as a stack of these wires. While some wires may link end-to-end to form loops, others remain unconnected. The quality of such a superconductor cannot be guaranteed. Some regions in an LK-99 sample might exhibit superconductivity, while others may not follow suit. When subjected to an external magnetic field, loop currents may be induced in the superconducting regions to counteract the applied field, resulting in diamagnetism, whereas the non-superconducting regions succumb to gravitational pull.

Probably, superconducting segments are not evenly distributed but rather concentrated in small regions of a sample. This could explain why superconducting properties are more pronounced in small LK-99 specimens. The typical superconductivity properties, such as the Meissner effect and flux pinning, may be observable in samples with high concentrations of superconducting materials. The small percentage of superconducting segments in LK-99 specimens makes it difficult to observe these properties. This could explain the partial levitation and weak flux pinning observed in the videos from Korea University and Huazhong University of Science and Technology.

Measuring resistance in LK-99 samples is particularly challenging. Zero resistivity can only be detected if the measurement terminals are connected to a continuous, fully superconducting path formed by LK-99 crystals. Otherwise, the results may show variable resistivity depending on the specific region tested. When using a Kelvin bridge, four leads must connect three distinct sections of the sample along a complete circuit. If any section is not superconducting, the measurement will reflect that. The Southeast University team's results likely stem from variations in crystal quality across their sample, with one section only becoming superconducting below 110 K (−163 °C). This may also explain why superconductivity is sometimes not observed in single LK-99 crystals if the measurement setup fails to properly capture a superconducting path.

The premise of LK-99 is that the Cu atom could be accurately positioned. However, lead apatite contains many Pb atoms at different locations, which makes it challenging to substitute a specific Pb atom with a Cu atom in LK-99. Undesired impurities, such as Cu_2S, can easily be introduced into LK-99 during the synthesizing process, further complicating the matter. Some researchers believe that the inconsistent observations among different research groups can be attributed to these impurities. On the other hand, better synthesized LK-99 crystals, such as single LK-99 crystals, are unlikely to be superconductive because superconductivity in LK-99 is confined to a one-dimensional path, which does not provide a looping path for electron flow. The synthesis of high-quality LK-99 superconductors requires a carefully controlled crystal growth process to strike a balanced random arrangement of smaller crystals. These factors collectively underscore the inherent challenge of maintaining consistent quality for LK-99.

Among all the challenges, the localized one-dimensional superconductivity in LK-99 is a fundamental limitation that constrains its excellence. This limitation is rooted in the disconnectivity issue of electron tunnels with complex molecules, as mentioned in the preceding section. Therefore, LK-99 does not represent the optimal embodiment of the engineering principle outlined previously. It should be avoided based on the guidelines.

This anisotropic superconductivity is typical in type-II superconductors, making them susceptible to magnetic fields in various directions. For example, cuprate superconductors often exhibit a perovskite-like structure, characterized by distorted, oxygen-deficient multilayered arrangements. These oxide compounds typically feature alternating layers of CuO_2 planes, with superconductivity occurring between them. The critical temperature tends to increase with a greater number of CuO_2 layers. In superconductors like YBCO, superconductivity predominantly occurs along the CuO_2 planes, although it can also be disrupted at crystal grain boundaries. Despite this, the two-dimensional nature of superconductivity in YBCO renders it more robust compared to the one-dimensional superconductivity observed in LK-99.

The electron tunnel theory reveals the microscopic mechanism underlying superconductivity, emphasizing that the key to achieving superconductivity is the reduction of intermolecular spacing. LK-99 has made substantial progress in bringing to life the concept proposed based on this theory. Specifically, this approach involves the deliberate adjustment of molecular structures to harness molecular attraction in opposition to repulsion, effectively compacting the molecular spacing to achieve superconductivity without relying on external pressure.

The significance of LK-99 is that it has changed the engineering philosophy in the development of room-temperature superconductors. Previously, the focus was on using external pressures to overcome the repulsion and reduce the spacing between molecules. LK-99 showed an alternative approach to achieve room-temperature superconductivity by utilizing molecular forces instead. In doing so, it has not only paved a new trajectory but also marked a remarkable advance in the progression of room-temperature superconductor research.

It is important to recognize the presence of various alternative methodologies for inducing molecular compression. A more refined implementation of the outlined principle for synthesizing superconductors lies just on the horizon.

Further Discussions

The most challenging part for some readers lies in the departure from the traditional resistance model ingrained within our current knowledge framework, established from school textbooks. The widespread conviction in this model, without questioning its validity over centuries, poses a significant hurdle. This steadfast adherence might be a contributing factor to our prolonged inability to fully comprehend the mechanisms of superconductivity and to successfully engineer room-temperature superconductors.

This educational article deliberately sidesteps theoretical intricacies and simplifies some of the concepts, opting for a concise approach. Supplementary literature on this topic is provided below for those seeking a deeper dive. We welcome constructive feedback from anyone interested in this topic. By collectively discussing and sharing ideas, we can advance our understanding of nature and move closer to the early discovery of room-temperature superconductors, which would be a significant benefit to humanity.

Revision History

- 08/28/2023: Initial Post on Stanford Site.
- 11/02/2025: 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)
- The Triangle of Energy Transformation (PDF: DOI) (中文: DOI)
- Is Thermal Expansion Due to Particle Vibration? (PDF: DOI) (中文: DOI)
- Superfluids Are Not Fluids (PDF: DOI) (中文: DOI)
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- Entropy Can Decrease (PDF: DOI) (中文: DOI)
- The Restoration Principle (PDF: DOI) (中文: DOI)
- Is There a Sea of Free Electrons in Metals? (PDF: DOI) (中文: DOI)
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