

# Superfluids Are Not Fluids

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## Abstract

At 2.17 K, the  $\lambda$ -point, helium undergoes a dramatic transformation: it loses all viscosity and becomes a “superfluid”, exhibiting extraordinary behaviors that defy conventional fluid dynamics. This study explores the fundamental physics underlying these phenomena. Unlike most substances, whose molecules are held together by intermolecular forces responsible for solidity and fluid viscosity, helium superfluidity arises from the absence of such attractions. Due to its simple and symmetric atomic structure, helium is largely immune to intermolecular forces except for the weak London dispersion force, which itself vanishes at sufficiently low temperatures. As a result, helium atoms in the superfluid state experience no mutual attraction and move as independent particles, leading to zero viscosity. Thus, a superfluid is not a traditional fluid but a collection of unbound atoms. The transition to the superfluid state requires breaking residual intermolecular bonds, which consumes energy and lowers the temperature, causing the transition to span a range rather than occurring at a constant temperature. Thus, the  $\lambda$ -point marks the completion of this transition, which likely begins at temperatures above 2.6 K. This interpretation is supported by the observed curvature in specific heat near the  $\lambda$ -point. The absence of intermolecular attraction in superfluid helium also explains why it cannot solidify merely by cooling. However, helium can be solidified under high pressure, suggesting the formation of a novel type of bond, termed a “compression bond”, resulting from the deformation of electron clouds under extreme pressure. More broadly, such bonds may also play a role in holding atoms together in metallic hydrogen and could offer insight into the bonding mechanisms in other metals.

## Introduction

The helium-4 superfluid was discovered in 1937.<sup>[1]</sup> To obtain this superfluid, helium-4 liquid is typically cooled through evaporation. To accelerate the cooling process, helium vapors are vacuumed from the container. Evaporation occurs not only on the surface but also within the liquid, causing helium bubbles to rise like boiling water. This boiling ceases abruptly when the temperature reaches 2.17 K, known as the  $\lambda$ -point,<sup>[2]</sup> which is commonly regarded as the transition temperature of helium-4 from a liquid to a superfluid. Beyond this point, many superfluid phenomena become observable. For example, a thin film of helium can defy gravity by creeping over the walls of its container.<sup>[3]</sup> This study will explain this and other abnormal phenomena associated with superfluid helium-4.

Superfluidity is often associated with Bose-Einstein condensation, leading to the theory that the formation of a helium-4 superfluid is related to the formation of a Bose-Einstein condensate. However, this is not accurate. Not all Bose-Einstein condensates are superfluids, nor are all superfluids Bose-Einstein condensates.<sup>[4]</sup> This theory faced further challenges when superfluidity was observed in helium-3,<sup>[5]</sup> whose atoms are fermions and cannot form Bose-Einstein condensates. The theory was adjusted to suggest that superfluidity in helium-3 arises from the pairing of helium-3 atoms into composite bosons.<sup>[6]</sup>

There is also a suggestion that both superfluidity and superconductivity result from the same underlying mechanism. In the Bardeen-Cooper-Schrieffer (BCS) theory, Cooper pairs of electrons bound together at low temperatures explain superconductivity.<sup>[7]</sup> However, this theory faces challenges as it cannot account for high-temperature superconductors, which operate at temperatures much higher than theoretical predictions. To address these issues, a new theory was proposed to explain both low- and high-temperature superconductivity, as well as normal resistivity, in a unified framework,<sup>[8]</sup> suggesting that superconductivity is unrelated to superfluidity.

Clues are revealed in the atomic structure of helium, which determines its intermolecular forces. Additional information from the measurement of helium-4 specific heat also provides more insight into superfluid transitions. These findings shed new light on superfluidity, inspiring us to propose an alternative theory for superfluidity. With this theory, all observed phenomena of superfluids can be explained. The theory also suggests that helium solids cannot form without pressurizing the helium and predicts the existence of a novel type of bond, named the compression bond, which is responsible for holding molecules together in helium solids at high pressures.

### **Extraordinary Properties of Superfluidity**

Superfluidity is traditionally characterized as a fluid with zero viscosity. When stirred, superfluids will continue to flow indefinitely. The viscosity of a fluid is defined as its resistance to deformation at a given rate and is usually conceptualized as quantifying the internal frictional force that arises between adjacent layers of fluid in relative motion. However, this analogy is misleading, as it implies that viscosity results from molecules colliding with each other. In reality, such collisions are unlikely because the repulsion between molecules increases rapidly as the distance between them decreases. Instead, viscosity is caused not by friction but by the attraction between molecules. Intermolecular attractions make fluids cohesive and resist flow.

At a macroscopic scope, an individual molecule appears electrically neutral. However, an uneven distribution of electrons within a molecule, especially in polyatomic molecules, introduces variations in electrical fields. The electron clouds may further redistribute due to the fields of adjacent molecules, creating local regions of positive and negative charge. These regions begin to exert force on adjacent molecules, giving rise to intermolecular forces. Initially attractive, these forces become repulsive within Van der Waals' distance.<sup>[9]</sup> Different types of forces are characterized by various properties and account for the viscosity of different fluids.<sup>[10]</sup> For instance, hydrogen bonds determine the viscosity of water and the formation of ice. Among all the types, the London dispersion force is particularly important for understanding helium superfluids. It is a relatively weak force, but more universal, and becomes significant only when other forces are not present.

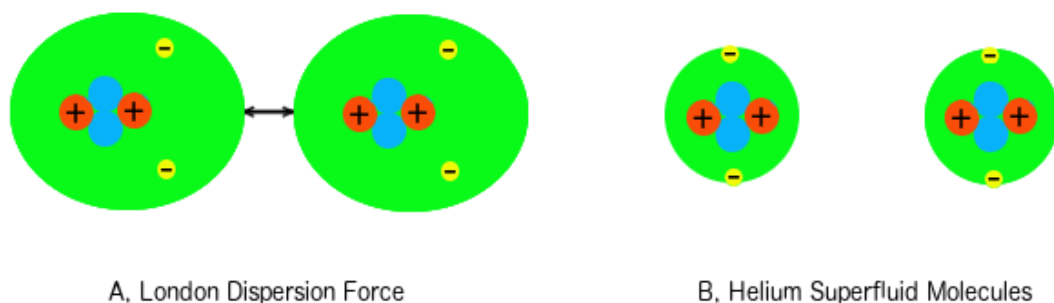
The force of attraction between molecules of the same type is known as cohesion, while adhesion refers to the attraction between fluid molecules and their surrounding surfaces, such as those of a container. Surface tension is a manifestation of cohesion at the liquid-air interface. Capillarity is a result of adhesion. Viscosity is mainly influenced by cohesion, as the molecules in a fluid are drawn together by the forces from their neighboring molecules during movement. All these forces originate from intermolecular attractions, and each contributes uniquely to different superfluid phenomena.

Unlike ordinary liquids, which exhibit viscosity due to the cohesive forces between molecules, superfluids lack viscosity because these cohesive forces are absent. Properties such as viscosity, cohesivity, and surface tension are all

manifestations of intermolecular attractions. When these attractions are absent, these properties disappear, leading to the remarkable phenomena observed in superfluids. The absence of attraction between particles is the defining characteristic of superfluids. Achieving this state is rare because intermolecular attraction forces are nearly inevitable, making superfluids exceptionally uncommon. This state has been primarily observed in helium, where, at low temperatures, intermolecular attractions and London dispersion forces vanish. Therefore, a superfluid is not a traditional fluid but rather a collection of molecules with no intermolecular attractions.

### Vanishing of Viscosity

The London dispersion force is a weak yet ubiquitous intermolecular force. In helium molecules, the electron clouds fluctuate over time, causing instantaneous disturbances in the electrical fields that alter the spatial distribution of orbital electrons in neighboring molecules. This induction effect propagates from one molecule to another, leading to polarization and the formation of dipoles in each molecule. The attraction between the positive end of one molecule and the negative end of another is known as the London dispersion force, named after the physicist Fritz London.<sup>[11]</sup> Since the two electrons in a helium molecule fully occupy the valence orbital, the even distribution of its electron cloud makes helium less susceptible to all other intermolecular attractions except for the London dispersion force. In the absence of other intermolecular forces in helium liquids, the weak London dispersion force becomes the predominant interaction between molecules, contributing to the liquid's viscosity.



**Figure 1: Disappearance of intermolecular attraction and viscosity in superfluids.** A) Due to the even distribution of electrons in helium atoms, there are no other interactions between helium molecules except for London dispersion forces. These forces create attractions between the molecules, contributing to the viscosity of helium liquids. B) At low temperatures, electrons occupy lower energy orbitals, and the stronger attraction between electrons and their nuclei reduces their dispersion. When the temperature drops to 2.17 K, London dispersion forces become negligible, resulting in the disappearance of intermolecular attractions and viscosity.

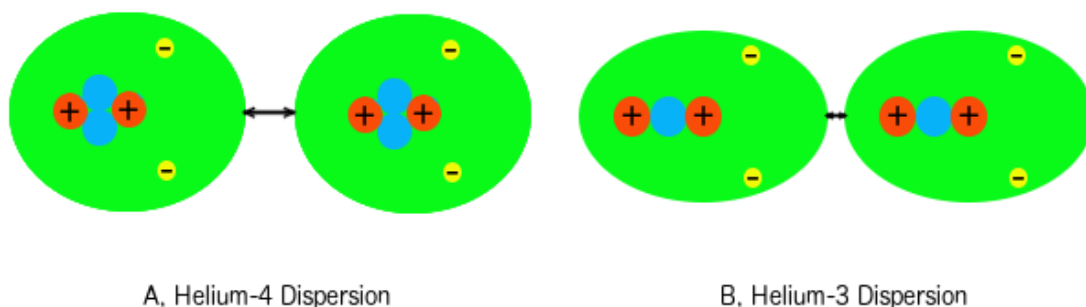
Figure 1A shows the attraction between two helium molecules due to the London dispersion force. At high temperatures, the excited electrons in helium molecules occupy high-energy orbitals that are distant from and less influenced by their nuclei. These electrons are more prone to perturbations, leading to London dispersion effects. Despite their weakness, the attraction between dispersed molecules is strong enough to impart cohesion and viscosity to the liquid. Conversely, at low temperatures, helium electrons move to lower orbitals and are more strongly attracted to their nuclei, reducing electron perturbation and weakening the London dispersion forces. When the temperature drops sufficiently, these dispersion forces become so weak that molecular interactions are negligible. Consequently, the attractions between molecules

vanish, as shown in Figure 1B. Without these attractions, helium molecules can move freely relative to one another, resulting in fluids with zero viscosity—a hallmark of superfluidity. In this state, helium is not a conventional fluid but rather a collection of individual molecules.

### Other Superfluids

Creating a superfluid involves eliminating intermolecular attractions. However, achieving this state in practice is extremely challenging because the Coulomb force is present wherever there is an uneven distribution of electrical fields. As long as valence electrons are not evenly distributed or do not fully occupy the outermost shell, there will be some intermolecular force stronger than London dispersion forces, which tends to overshadow the weaker London dispersion force. Consequently, there is usually some form of intermolecular force that generates viscosity in liquids. Therefore, the primary candidates for superfluids are elements in the noble gas group, which have fully occupied and evenly distributed valence electrons, making them less susceptible to other intermolecular forces except for London dispersion forces.

Among the noble gas elements, helium is the best candidate for forming superfluids due to its small atomic size, which causes its electrons to be strongly attracted to the nucleus. This tight electron attraction makes helium less susceptible to London dispersion forces than other noble gases. The attractions between helium molecules due to London dispersion are the weakest of all intermolecular forces. However, these attractions between helium-4 molecules are not completely eliminated until temperatures reach very low levels, specifically 2.17 K. In contrast, helium-3 transitions to a superfluid state at an even lower temperature, around 0.0025 K.<sup>[12]</sup> Despite being the same element, the significant difference in their transition temperatures, by a factor of approximately 1,000, raises the question of why this disparity exists.



**Figure 2: Impact of helium nuclear structure on superfluid transition temperature.** Helium-4 has a superfluid transition temperature, i.e., 2.17 K, while helium-3 transitions at a much lower temperature, i.e., 0.0025 K. This difference is due to the difference in nucleon configurations between the two isotopes. A) In a helium-4 atom, two neutrons hold two protons closely. B) However, with only one neutron holding two protons against their repulsion in a helium-3 atom, the two protons spread apart in opposite directions, elongating the electron cloud of the helium-3 atom. As a result, the London dispersion forces in helium-3 atoms are stronger and disappear at a much lower temperature. NOTE: At the quantum scale, the nuclear configuration is in constant dynamic fluctuation. The figure above represents only the average configuration. Can the nuclear attraction between two protons overcome their Coulomb repulsion? If it could, the three nucleons in helium-3 would arrange themselves in a triangular configuration. This situation suggests that two protons could potentially form a stable nucleus without the need for a

neutron. However, stable helium isotopes with only two protons in the nucleus have never been observed, indicating the triangular configuration is unlikely.

The difference lies in the nucleon configurations between the two helium isotopes, which influence the intensity of their London dispersion forces. In a helium-4 atom, two neutrons tightly bind the two protons together, as illustrated in Figure 2A. In contrast, a helium-3 atom has only one neutron pulling the two protons. The repulsion between the two protons causes them to spread apart in a linear arrangement on the opposite sides of the neutron, as illustrated in Figure 2B. This layout makes helium-3 more susceptible to London dispersion forces. At the same temperature, the electron cloud in a helium-3 atom is more elongated than in a helium-4 atom, leading to stronger London dispersion forces between helium-3 atoms. Consequently, the attractions between helium-3 molecules are not diminished until much lower temperatures.

Based on this theory, we can qualitatively predict that the transition temperature for helium-5 will be higher than that of helium-4. The optimal average nucleon configuration for a helium-5 atom, given the repulsion between protons and the attraction between protons and neutrons, is likely to feature three neutrons arranged in a triangular layout with the two protons positioned on opposite faces of the triangle. Consequently, the distances between the protons in helium-3, helium-4, and helium-5 should approximate the ratio  $\sqrt{12}:\sqrt{9}:\sqrt{8}$ .

If the helium superfluid transition temperature is inversely correlated to the distance between the protons in the isotopes, we should expect the transition temperature for helium-5 to be slightly higher than helium-4. With known transition temperatures of 0.0025 K for helium-3 and 2.17 K for helium-4, the transition temperature for helium-5 is estimated to be roughly 2.93 K.

Additionally, superfluidity could potentially be observed in other noble gas elements. However, our theory indicates that the transition temperature generally decreases as atomic size increases. Given their larger atomic sizes and increased susceptibility to London dispersion forces, these elements are expected to have significantly lower transition temperatures than helium-3.

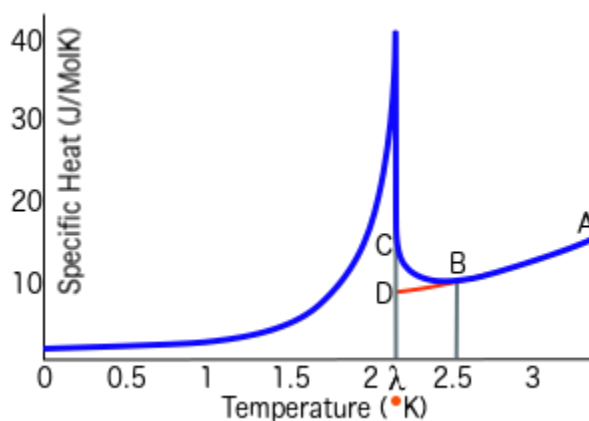
### **Variable Temperature Phase Transition**

Phase transitions involve changes in the bond structure between molecules, such as bond rearrangement during melting or bond breaking during sublimation. A phase transition is defined as the period from the first change in bonds to the completion of the last change. It is commonly observed that a phase transition occurs at a constant temperature. Breaking bonds requires energy, and transitioning to a higher temperature phase also demands energy. These two processes compete for energy. For example, in the melting of ice into water, latent heat is absorbed to break the hydrogen bonds, which impedes the temperature rise. Essentially, whenever a phase transition and the associated bond changes compete for energy, they slow down the temperature change, causing the temperature to remain constant during the transition.

In addition, for the temperature to remain constant during a phase transition, the process must also occur slowly enough to allow an anchor effect<sup>[13]</sup> to propagate throughout the system. This effect arises primarily because the extension of intermolecular bonds reaches a physical limit, producing a stabilizing anchor effect. As energy is added, these bonds stretch and accumulate potential energy, while their structural strength gradually weakens. Eventually, they can no longer resist the growing intensity of transimpacts<sup>[14]</sup> and begin to break, signaling the onset of the phase transition. At this point,

the system's potential energy reaches a plateau, and the radiation emitted by the strained bonds stabilizes. Because temperature reflects the system's radiation level, it remains steady throughout the transition.

However, according to our observation, superfluid transitions do not occur at a fixed temperature. During a superfluid transition, bonds break as the system moves to a lower-temperature phase, and these processes do not compete for energy. Bond breaking withdraws energy from the system, facilitating the temperature decrease necessary for the transition. Therefore, we predict that the temperature will drop during the superfluid transition. In other words, the  $\lambda$ -point around 2.17 K should not be seen as a constant temperature characteristic of superfluid transitions, as is often assumed in conventional transitions, but rather as the endpoint temperature of the transition. This view is supported by the unusual shape of the specific heat curves, as shown in Figure 3.



**Figure 3: Identifying the start temperature of helium-4 superfluid transitions.** The blue  $\lambda$ -shaped curve illustrates the specific heat of helium-4 at saturated vapor pressure relative to temperature. Notably, the significant curvature disparity between the two sides near the  $\lambda$ -point suggests that superfluids exhibit a higher specific heat compared to helium liquids. In the absence of any superfluid presence to the right of the  $\lambda$ -point, the curve would typically follow a similar downward trend from point A to point B, and then to point D. However, the observed increase in specific heat from point B to point C deviates from this trend. This elevated specific heat above the red trendline could potentially be attributed to newly formed superfluid molecules. The initiation of the superfluid transition might occur at point B or even earlier, where London dispersions weaken sufficiently for the associated normal helium molecules to begin dissociating into individual superfluid molecules.

The transition to a helium superfluid is marked by a final temperature of approximately 2.17 K, evidenced by the sudden stop of boiling in experimental observations. Boiling bubbles form because surface tension encloses air chambers within the helium vapor, suggesting the presence of intermolecular attractions. However, once the superfluid state is reached, London dispersion forces are no longer effective, and there is no attraction between helium molecules to sustain surface tension for bubble formation.

In normal helium liquid, heat is transferred through convection and bubbling, similar to other liquids. After the bubbles disappear, heat transfer continues via convection, but in a different manner. Rather than ordinary viscous circulation, convection transitions to a direct flow of individual molecules.<sup>[15]</sup> This change in heat transfer mode also signals the absence of intermolecular attractions and viscosity.

The conclusion of the transition is also marked by a spike in specific heat. Figure 3 illustrates the specific heat of helium-4 liquids at saturated vapor pressure as a function of temperature.<sup>[16]</sup> The blue curve of the specific heat shows a discontinuous spike at 2.17 K, taking the shape of the Greek letter lambda, hence the name  $\lambda$ -point. Therefore, the end of the helium-4 superfluid transition at the  $\lambda$ -point is clearly evidenced by the disappearance of vapor bubbles, the change in convection mode, and the spike in specific heat.

The starting temperature of a transition is ideally marked by the first change in bonds, but the gradual nature of superfluid transitions makes this initial change difficult to identify precisely. During a helium superfluid transition, thermal energy must be removed from the system to lower its temperature. As energy is extracted from the helium liquid, the temperature decreases, causing the bonds between liquid molecules to weaken and break due to the disruption of London dispersion forces. The absorption of energy during bond breaking further reduces the liquid temperature. Consequently, the system cannot maintain a fixed temperature during the transition.

The superfluid transition differs from the ice-water transition: in the latter, the energy required to break hydrogen bonds between water molecules hinders temperature change, resulting in a transition at a constant temperature. In contrast, the superfluid transition involves a continuous decrease in temperature. During this process, the number of intermolecular bonds decreases, and the transition completes when all bonds are broken. This endpoint is marked by the  $\lambda$ -point in Figure 3 and the observation of superfluid properties beyond that point.

Nevertheless, the starting temperature of the helium superfluid transition may be roughly identified by analyzing the helium-specific heat curve. As energy is removed from the helium liquid, the specific heat typically decreases starting from point A. For homogeneous liquid molecules to the right of the  $\lambda$ -point, the specific heat curve is expected to follow a similar downward trend from A to B and D, as illustrated by the extension of the red curve. However, the trend changes at point B. The significant upward curvature from B to C indicates a much higher specific heat, suggesting the onset of the phase transition in the liquid.

In liquid helium, energy is primarily stored in three components: intermolecular bonds, orbital electrons, and the motion of particles. Under normal conditions, the specific heat curve should display a smooth downward trend if none of these components undergo significant changes. Therefore, a noticeable change in the curvature of the curve suggests a shift in one or more of these energy-storing mechanisms. Since neither the orbital electrons nor the kinetic energy of particles are expected to change substantially in this temperature range, the curvature shift is most likely caused by the breaking of intermolecular bonds as London dispersion forces weaken. This bond dissociation reduces the number of bound molecules and increases the population of superfluid molecules.

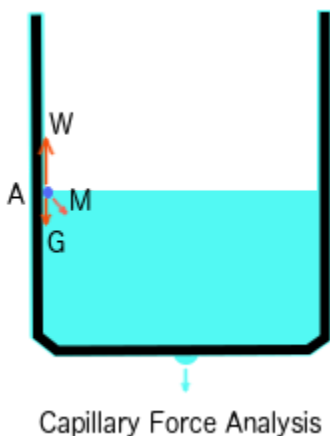
The significant increase in specific heat to the left of the  $\lambda$ -point suggests that superfluid molecules possess a higher specific heat capacity compared to normal helium molecules. The upward curvature of the specific heat trend starting from point B serves as evidence of increasing superfluid molecules. This is further supported by experiments where escalating efforts are required to lower the temperature towards the  $\lambda$ -point. As the system approaches the  $\lambda$ -point, the number of superfluid molecules within the system increases, and the specific heat begins to resemble that of the superfluid side of the curve. The increasing upward curvature of the specific heat indicates the accelerated rate of superfluid conversion nearing the  $\lambda$ -point. If heat is steadily removed from the system, the time required to decrease the temperature should lengthen as it approaches the  $\lambda$ -point, a phenomenon observed in experiments.

Determining the onset temperature of the superfluid transition typically aligns with the point where normal helium molecules start to dissociate into superfluid molecules, which should be signaled by a change in the curvature of the specific heat. However, the sensitivity of the specific heat curvature is limited in the initial stages. The initial conversion of helium molecules to superfluid molecules may be scarcely discernible in the specific curvature. Transition progresses gradually, complicating the identification of a definitive starting point for the phase transition. While a noticeable change in curvature occurs around point B, approximately at 2.6 K, designating it as the transition's initiation point is somewhat arbitrary. The actual onset temperature of the phase transition likely occurs at a considerably higher temperature.

Essentially, a superfluid transition differs from most conventional phase transitions by its variable temperature nature, as opposed to the constant temperature characteristic of typical transitions. Throughout this transition, both normal fluid and superfluid phases coexist. This transitional range may correspond to where reduced viscosity is observed, providing a basis for the two-fluid model commonly discussed in the literature. Beyond zero viscosity and variable transition temperature, this theory offers explanations for various other superfluid properties and phenomena, which we will delve into in the upcoming sections.

### Defying Gravity

An intriguing observation in helium superfluids is the phenomenon of helium creeping over the rim of its container against gravity, as depicted in Figure 4. To unravel the physics underlying this behavior, let's dissect the forces acting on an individual molecule. Consider a helium molecule situated near the container's wall at point A. It experiences three forces:  $W$ , the upward adhesion to neighboring molecules of the container;  $G$ , the downward force comprising the molecule's weight, adjusted by the buoyancy if it resides in the fluid; and  $M$ , the cohesion with surrounding helium molecules within the container. In helium liquid, cohesion ( $M$ ) arises from London dispersion forces. Conversely, in superfluids, where London dispersion forces are negligible, cohesion diminishes to zero, i.e.,  $M = 0$ .



**Figure 4: The creeping phenomenon of superfluids.** This phenomenon involves superfluids defying gravity by creeping along the walls of their container. At point A within the container, a helium molecule experiences an upward pull from the adhesion force to the container,  $W$ , alongside the downward force of gravity,  $G$ . In superfluids, the cohesion force  $M$  becomes negligible due to the absence of London dispersion forces. With cohesion absent,

the molecules of the superfluid are drawn upward by those on the container wall, as Coulomb's force  $W$  vastly outweighs gravity  $G$ .

Despite the absence of cohesion among superfluid molecules, adhesion may persist between the superfluid and its container. Consider a container crafted from glass, such as  $\text{SiO}_2$ , where oxygen and silicon atoms are bound by covalent bonds, leading to an uneven distribution of electrons within silicon dioxide and the emergence of local fields. The positive regions of these fields engender adhesion to the superfluid molecules. Hence,  $W$  represents the adhesion stemming from this form of interaction.

Coulomb's force vastly outweighs gravity, rendering  $G$  insignificant compared to  $W$ . Therefore, in the absence of cohesion within the superfluid, the net force propels the molecule upward along the container wall. Consequently, a thin layer of superfluid molecules coats the container's entire surface. However, intermolecular forces operate primarily at short distances. As the helium film thickens, gravity overtakes, causing the excess superfluid to descend along the container wall, as depicted in Figure 4, eventually leading to drips off the container's bottom.

The creeping effect is not exclusive to superfluids; it can also manifest when  $M$  is extremely small. Whenever the combined force of  $W$ ,  $G$ , and  $M$  tilts upwards, liquid molecules are drawn upward. Comparable creeping phenomena are observed in substances like alcohol and gasoline. This phenomenon also explains why the water level rises along the edges of its container, as adhesion tugs the water molecules upward. However, molecules may not ascend too high because they're simultaneously pulled downward by cohesion with surrounding water molecules. When a narrow tube is immersed in water, the water within the tube may rise significantly above the surrounding water level due to adhesion, a phenomenon termed capillarity. This occurs because the number of adjacent water molecules is restricted horizontally by the tube's diameter, resulting in reduced downward cohesion. Thus, both superfluid creeping and capillary effects stem from the same underlying mechanism.

### **Superleak Phenomenon**

Superleak refers to the phenomenon wherein superfluids can permeate through nanoporous membranes, a feat unachievable by ordinary fluids. The pores of these membranes measure approximately 0.7 nm in diameter, roughly three times the size of liquid helium molecules. Adhesion between superfluid molecules and the membrane surfaces results in a layer of superfluid molecules adhering to the entire membrane surface, thereby diminishing pore size. Consequently, the effective diameter of the pores becomes comparable to that of liquid molecules. Given that electrons of superfluid molecules occupy lower orbitals, superfluid molecules possess a smaller size compared to liquid molecules, as depicted in Figure 1. Consequently, individual superfluid molecules can freely traverse through the membranes.

Owing to the cohesive forces among helium molecules in liquid form, further helium molecules adhere to the initial layer on the membrane's surface, augmenting the thickness of the helium layer and subsequently diminishing the pore size even more. Consequently, the pores become effectively obstructed as they are filled by these molecules, thereby impeding the flow of helium liquids through the membranes.

The velocity of superleaks has been observed to diminish with increasing temperatures. The presence of helium-liquid molecules reduces the pore size and accounts for the decreased flow rate at higher temperatures. As the temperature rises, the flow diminishes and eventually halts. As previously discussed, the transition of helium-4 into a superfluid occurs

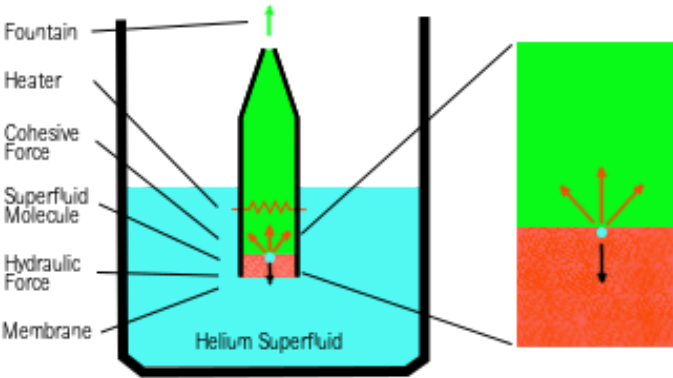
within a range from approximately 2.6 K to 2.17 K, during which both helium liquid and superfluid molecules coexist. The decline in flow rate should be evident within this temperature range.

### Fountain Effect

Another intriguing phenomenon involving superfluids is the fountain effect. This phenomenon is demonstrated by suspending a tube containing a nanoporous membrane plug at its lower end within a bath of helium superfluid. The superfluid can permeate the tube through the membrane. Upon heating, the helium ascends through the tube and emerges in a fountain-like manner, as illustrated in Figure 5. What drives this fountain effect mechanism?

The superfluid flows through the membrane, maintaining uniform fluid levels inside and outside of the tube, behaving according to normal hydraulic principles. Upon heating concentrated inside the tube, the superfluid undergoes a transition into normal helium liquid, triggering cohesion among the molecules through London dispersion. This cohesion acts as a barrier, halting the escape of the helium liquid back out of the tube through the membrane, effectively converting the membrane into a one-directional check valve that exclusively allows the superfluid to enter the tube. However, this effect alone isn't adequate to drive the fountain effect.

To comprehend the other aspect of the fountain effect, let's consider a superfluid molecule depicted as a blue dot within a pore near the top of the membrane, as illustrated in Figure 5. As the superfluid inside the tube is heated and transforms into normal helium liquid, these helium molecules begin to exhibit cohesion due to London dispersion forces. Specifically, the blue superfluid molecule absorbs heat from above and swiftly transitions into a normal helium molecule, which then forms cohesion with other converted molecules above it. In the absence of cohesion from the superfluid molecules below, the blue molecule will be drawn out of the pore by the upper molecules. The subsequent superfluid molecule beneath the blue one promptly fills the gap, initiating a cycle that continuously pumps molecules into the tube.



**Figure 5: Fountain effect of superfluids.** To initiate a fountain effect, a superleak is fashioned utilizing a nanoporous membrane positioned at the tube's base. Within the membrane, a superfluid molecule, denoted by a blue dot, resides near the top of a pore. Upon heating from above, the molecule transforms into a normal liquid molecule, becoming susceptible to cohesion with the liquid above it. In the absence of downward attraction from the superfluid below, cohesion effectively draws the blue molecule out of the pore, functioning akin to a pump. As additional molecules amass within the tube, they are ultimately expelled from the top, creating the fountain effect.

As superfluid molecules continue to be pumped into the tube, a hydraulic head forms inside, generating a downward force on the blue molecule that opposes the upward cohesion. Nevertheless, the upward cohesion arising from Coulombic forces outweighs the downward hydraulics. If the tube isn't excessively tall, the hydraulic force is unable to hinder the accumulation of helium, eventually resulting in its expulsion at the top, thus instigating the fountain effect.

## Second Sound

Sound manifests as a form of vibration that propagates as an acoustic wave through a transmission medium, whether it be gas, liquid, or solid. The generation of an acoustic wave necessitates cohesion among molecules within an elastic medium. However, given the absence of such cohesion among molecules in a superfluid, the formation of an acoustic wave is precluded. Consequently, vibrations within a superfluid do not propagate as acoustic waves but rather as pulses or within resonant cavities via direct molecule flow.

In conventional fluids, heat is commonly transferred through convection of fluid motion or conduction in a diffusion manner, facilitated by the cohesion among molecules. However, in superfluids, where cohesion between molecules is absent, heat is conveyed through the convection of individual molecules' direct flow. This phenomenon is termed the second sound, as the wave motion of entropy and temperature is similar to the propagation of pressure waves in air. The effective conduction velocity can be notably high, reaching up to 20 cm/s.

## Predictions

Thus far, the proposed theory has proven instrumental in comprehending and explaining observed superfluid phenomena. Several predictions naturally stem from the theory, enabling us to further substantiate its validity. Firstly, it is widely recognized that the viscosity of most liquids escalates as temperature decreases. However, the proposed theory anticipates distinct trends for helium. The viscosity-temperature curve for helium-4 should exhibit variation in the three sections surrounding the  $\lambda$ -point. As the temperature declines, the viscosity should increase typically, akin to other liquids in the liquid phase, reaching its peak until the onset of the superfluid transition at approximately  $\sim 2.6$  K. Subsequently, it should decrease during the transition phase, ultimately converging to zero at the  $\lambda$ -point around 2.17 K, and persisting at zero in the superfluid segment.

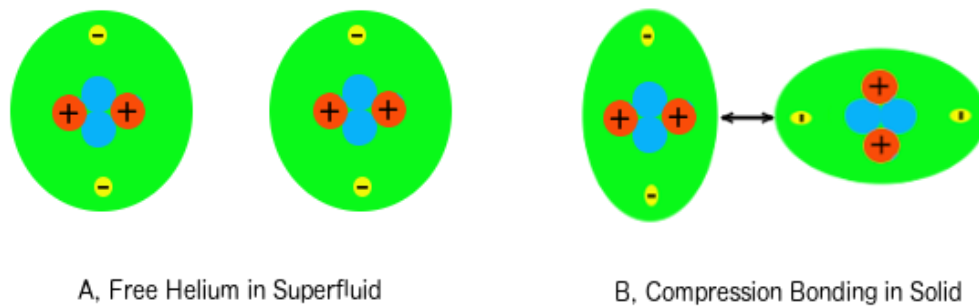
Secondly, even in the absence of gravity, water molecules can still aggregate to form droplets due to cohesion. However, this phenomenon should not be anticipated in superfluids. Thus, when superfluids are released in a gravity-free or microgravity setting, such as in a spacecraft, droplets are not anticipated. Instead, individual molecules will disperse into space. This dispersion might give the impression that the superfluid has evaporated. However, there is no actual phase change; the appearance of evaporation is merely due to the absence of cohesion between superfluid molecules that would typically bind them together.

Another prediction concerning superfluids is their inability to solidify at low temperatures, even at 0 K, in the absence of pressure. This is attributed to the lack of intermolecular attraction within superfluids, rendering them incapable of bonding to form solids irrespective of temperature. The liquid-like appearance of superfluids primarily results from gravitational effects, prompting molecules to congregate at the bottom of their container. This contrasts with helium liquid molecules, which are bound together elastically by cohesion.

Nevertheless, it has been reported that a helium-4 solid has been obtained at temperatures around 1-1.5 K, but with a high pressure (>2.5 MPa).<sup>[17-18]</sup> Under normal pressures, helium liquid would typically transition into a superfluid at these temperatures. Generally, intermolecular attractions are requisite for any viscous fluid. The absence of such attractions results in a fluid becoming a superfluid. Similarly, intermolecular attractions are essential for any solid; lacking them, there would be no solid, only a "fine powder" of molecules. To withstand shear stresses, molecules in solids must be bound together in some manner. Given the absence of cohesion between superfluid molecules, merely packing them together would not yield solids capable of resisting shear stresses. Therefore, the question arises: How can high pressure transform helium molecules into solids?

Our prediction posits the existence of a novel bond that binds helium molecules together in helium solids. Under high pressures, helium molecules undergo compression, causing the electron cloud of each molecule to contract along the axis defined by the two protons, in response to the repulsive forces of electric fields emanating from neighboring molecules. This compression results in an uneven distribution of electron density in various directions, generating local fields that are positive towards the ends of the axis defined by the protons and negative towards the periphery of the plane perpendicular to that axis. This disparity induces an attractive force between these fields. Driven by this force, molecules reorient themselves to minimize their potential energy. Ultimately, the system stabilizes at a configuration of low potential energy between molecules, as depicted in Figure 6B. This bond is termed a compression bond.

Figure 6B depicts the smallest chain of two molecules bound together by this compression bond. Numerous larger chains can extend from this foundational unit in diverse directions, generating amorphous structures characterized by low densities. With increasing pressure, these chains may be compressed into a more compact configuration, wherein the unit structure consists of four molecules bound together by compression bonds in a rotationally symmetric arrangement. In such a compact structure, helium crystals with higher densities can be obtained.



**Figure 6: Formation of compression bond.** A) Under standard pressures, superfluids can be obtained from helium liquids by lowering the temperature. However, further decreasing the temperature does not lead to the production of helium solids because there are no attractive forces to bind the molecules together. B) Under high pressures, the electron cloud of each molecule contracts along the axis defined by the two protons. The resulting uneven distribution of electron density in various directions generates local electric fields, leading to an attraction between molecules. This phenomenon is termed the compression bond. Helium solids are expected to be composed of molecules bound together by this novel type of bond.

A helium solid has also been produced at room temperature, but under significantly higher pressures exceeding 113 GPa.<sup>[19]</sup> Under these extreme pressures, helium molecules are compressed to such an extent that London dispersions are disrupted and supplanted by compression bonds.

Compression bonds may also be present in solids composed of other elements. For instance, when subjected to pressures of approximately 400 GPa, hydrogen transitions into a metallic state.<sup>[20-21]</sup> Under these extreme pressures, the conventional covalent bonds between hydrogen atoms may be destabilized and supplanted by compression bonds, thus transforming hydrogen from a diatomic to a metallic form.

## Conclusions

This study offers new insights into the underlying physics of superfluidity and leads to three key findings:

- The distinctive properties of superfluids arise from the absence of interparticle attractions, giving rise to many of their unusual behaviors. In the case of helium, this lack of attraction between molecules is primarily due to its unique atomic structure, specifically, its small atomic size, fully occupied electron orbitals, and evenly distributed electron cloud.
- A superfluid phase transition does not occur at a fixed temperature. Instead, it involves the gradual breaking of intermolecular bonds, a process that consumes energy and leads to a further decrease in temperature. As a result, the transition unfolds over a temperature range, approximately between 2.17 K and 2.6 K for helium-4, rather than occurring at a constant temperature, as is commonly assumed at the  $\lambda$ -point.
- This study also predicts the existence of a novel type of intermolecular bond, termed a *compression bond*. In the absence of attractive forces, superfluids cannot solidify at low pressures, even at 0 K. However, under high pressures, the electron clouds of superfluid molecules become compressed and distorted, giving rise to these compression bonds. Although first proposed in the context of helium solids, such bonds may also be common in other solids composed of single-atom molecules, especially in metals.

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## Revision History

- [05/08/2021: 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)
- [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)
- [Why a Phase Transition Temperature Remains Constant](#) (PDF: DOI) (中文: DOI)
- [What Causes Friction to Produce Heat?](#) (PDF: DOI) (中文: DOI)
- [The Easiest Way to Grasp Entropy](#) (PDF: DOI) (中文: DOI)
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- [Is There a Sea of Free Electrons in Metals?](#) (PDF: DOI) (中文: DOI)
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