

# Theory of Superfluidity

Jerry Z. Liu

ZJL@CS.Stanford.EDU

Stanford University, California, USA

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## **Abstract**

The mystery of superfluidity has been revealed in our study of helium atomic structure. Its unique structure makes it possible to eliminate intermolecular attraction forces at low temperatures, resulting in zero viscosity -- a unique property of superfluidity. Further analysis of helium specific heat suggests that helium-4 transitions to superfluids within a range of temperatures from around 2.55°K to 2.17°K, rather than at a single temperature of the  $\lambda$ -point. These findings inspire us to hypothesize that a superfluid is a collection of individual particles without attraction between them. This theory offers an explanation for all the phenomena observed in superfluids and also predicts the existence of a novel type of intermolecular bonding, which is responsible for the formation of solid helium at high pressures.

## **Introduction**

The first superfluid is in helium-4 discovered in 1937 (1). In helium-4 superfluid experiments, liquid helium is often cooled via evaporation. To accelerate the cooling process, helium vapors are pumped out from their container. The evaporation takes place not only on the surface but also within the liquid. Helium bubbles rise like boiling water. The boiling stops suddenly when the temperature reaches 2.17°K, known as the  $\lambda$ -point (2), which is usually assumed to be the transition temperature of helium-4 from liquid to superfluid. From this point, many superfluid phenomena are observable. A thin film of helium can defy gravity by creeping over the wall of its container (3). This and other abnormal phenomena will soon be explained.

Superfluidity is often coincidental with Bose-Einstein condensation. Hence, the formation of a helium-4 superfluid is theorized to be related to the formation of a Bose-Einstein condensate. However, they are not related. Not all Bose-Einstein condensates can be regarded as superfluids, nor all superfluids are Bose-Einstein condensates (4). A further challenge to this theory arose later when superfluids were obtained in helium-3 (5). Helium-3 atoms are not bosons but fermions and cannot form Bose-Einstein condensates. An adjustment had to be made to the theory, suggesting the bosons are formed by pairing helium-3 (6). There is also a suggestion that both superfluidity and superconductivity are the results of the same mechanism. Cooper pairs of electrons bound together at low temperatures are used to explain superconductivity in Bardeen-Cooper-Schrieffer (BSC) theory (7). However, this theory is also facing challenges as it cannot account for the high temperature superconductors discovered recently. In the light of the additional evidence, a new hypothesis was proposed to explain both

superconductivity and regular conductivity in a unified theory (8), which does not relate superconductivity to superfluidity. Nevertheless, none of the existing theories can comprehensively explain all the phenomena observed in superfluids.

Clues are revealed in the atomic structure of helium that determines its intermolecular forces. Additional information about helium-4 specific heat also provides more insight into superfluid transitions. These findings cast a new light on superfluidity which inspired the author to propose a new theory of superfluidity. With this theory, all the abnormal phenomena of superfluids can be explained. The theory also suggests that solid helium could never be obtained without pressurizing the helium and predicts the existence of a novel type of bonding named compression bonding, which is responsible for the formation of solid helium at high pressures.

### **Theory of Superfluidity**

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

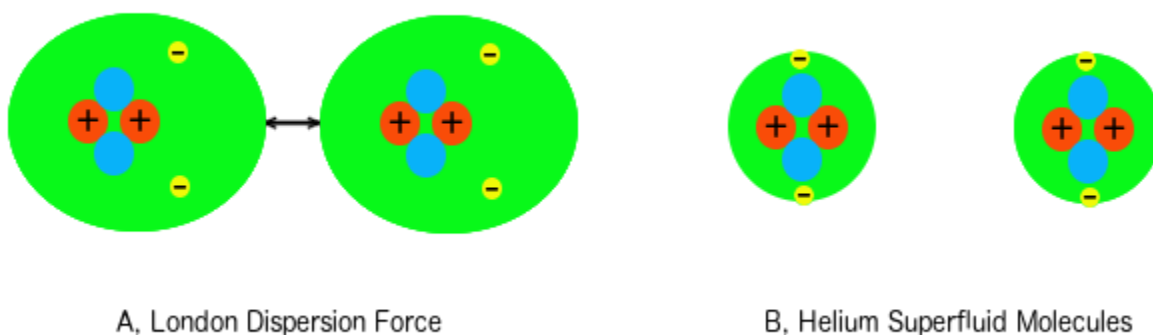
At a distance, an individual molecule appears electrically neutral. However, an uneven distribution of electrons within a molecule, especially for molecules composed of different elements, causes variations in its electrical field, creating local positive and negative regions. At short distances, these field regions begin to exert force on neighboring molecules, giving rise to intermolecular forces. The forces are at first attractive but become repulsive within Van der Waals' distance (9). Depending on their origin, attractive intermolecular forces are categorized into various types (10). Different types of forces are characterized with various properties and account for the viscosity of different fluids. For instance, hydrogen bonding determines the viscosity of water and the formation of ice. Among all the types, the London dispersion force is particularly important to the understanding of helium superfluids. It is a more universal but relatively weak force, which only becomes significant where other forces are not present.

The attraction between molecules of the same type is known as cohesion. Surface tension is cohesion on a liquid-air interface. Adhesion is the attraction between fluid molecules and their boundary, such as a container. Capillarity is a result of adhesion. Viscosity is primarily due to cohesion because molecules in a fluid are dragged by their neighbors in a relative motion. All these forces originate from intermolecular attractions, and each of these forces plays a different role in various superfluid phenomena.

With the above understanding and further studies of the intermolecular force and specific heat of helium, we postulate that a liquid is composed of cohesive particles and therefore viscous, whereas a superfluid is not liquid but a collection of individual particles (molecules or even subatomic particles) isolated from each other with no attractions between them. Fluid properties, such as viscosity, cohesivity, and surface tension, are different manifestations of intermolecular attractions. When the attractions disappear, so do these properties, which in turn lead to superfluid phenomena. Therefore, no attraction between the particles is the distinguishing characteristic of superfluids. Such a state is very difficult to achieve because intermolecular attraction forces are almost inevitable. This explains why superfluids are so rare. Nonetheless, this particular state has been discovered in helium where intermolecular attractions disappear along with diminishing London dispersions at low temperatures.

### Vanishing of Viscosity

In liquid helium, the London dispersion force dominates the interactions between the molecules and results in the viscosity of the liquid. The electron cloud of molecules undergoes fluctuations over time. These fluctuations create instantaneous disturbances in the electrical field that influence the spatial distribution of electrons orbiting nearby molecules. This induction propagates from one molecule to the next. Individual molecules are effectively polarized and become dipoles. The attraction arising between the positive end of one molecule and the negative end of another is known as the London dispersion force, named after physicist Fritz London (11). Since the two electrons in a helium molecule fully occupy the outermost orbital, the even distribution of its electron cloud makes helium less susceptible to all intermolecular attractions except for the London dispersion force. Fig. 1A shows the attraction between two helium molecules resulting from London dispersions.



**Fig. 1. Disappearance of intermolecular attractions and viscosity in superfluids.**

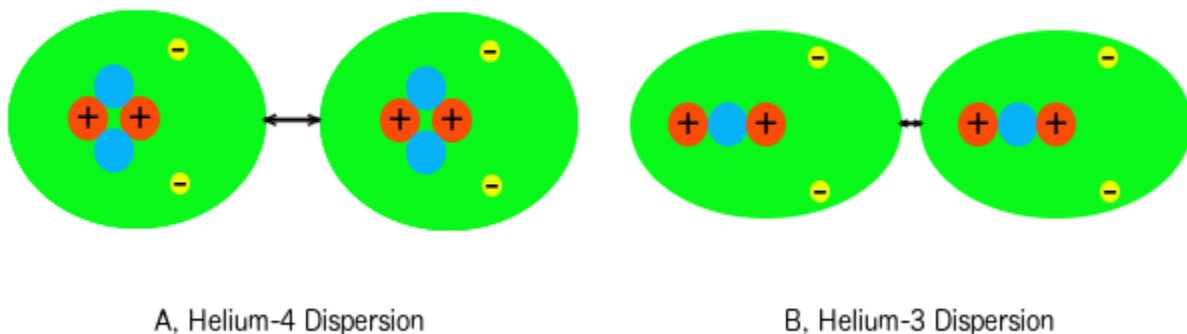
Because of the even distribution of electrons in a helium atom, there are no other interactions between the molecules but London dispersions. Attractions between the molecules arising from the dispersions make liquid helium viscous. The dispersions weaken at low temperatures where the electrons retreat to lower orbitals under tight

attractions from their nuclei. At 2.17°K, the dispersions become negligible, leading to the disappearance of intermolecular attractions and viscosity.

At high temperatures, the excited electrons in helium molecules occupy high energy orbitals far from and less influenced by their nuclei. These electrons are more susceptible to perturbations, resulting in London dispersions. Despite its weakness, the attraction between dispersed molecules is sufficient to make the molecules cohesive and liquid helium viscous. At low temperatures, helium electrons retreat to lower orbitals and are tightly attracted by their nuclei. Thus, the London dispersions are weakened. When the temperature is low enough, the dispersions become so weak that the interactions between molecules may be negligible. As a result, the attractions between molecules disappear as illustrated in Fig. 1B. Without the attractions, the molecules in helium fluids can move freely with respect to each other, resulting in fluids with zero viscosity -- a unique property of superfluidity.

### He-3 vs. He-4 Superfluid

In theory, a superfluid could be obtained from any fluid after eliminating attractions between the molecules. In reality, it is almost impossible to achieve such a state. The attractions between helium molecules resulting from London dispersions are the weakest force of all the intermolecular attraction forces. Even so, the attractions between helium-4 molecules are not eliminated until at a very low temperature, 2.17°K, while helium-3 superfluid transitions at a much lower temperature, 0.0025°K (12). Despite being the same element, why is there a 1,000 fold difference in the transition temperatures?



**Fig. 2. Impact of helium nuclear structure on superfluid transition temperature.** The superfluid transition temperatures are 2.17°K for helium-4 and 0.0025°K for helium-3. The difference is caused by the nuclear structures of the two helium isotopes. Two protons in a helium-4 atom are tightly glued by two neutrons in a compact layout. With a single neutron holding two protons against their repulsion in a helium-3 atom, the protons spread apart to the opposite sides of the neutron. This layout elongates the

electron cloud of helium-3 more than helium-4. The London dispersion forces in helium-3 are stronger and disappear at a much lower temperature.

The reason lies in the different nuclear structures between the two helium isotopes, which affect the intensity of their London dispersions. Two neutrons in a helium-4 atom hold two protons together in a compact layout as shown in Fig. 2A. With a single neutron holding two protons in a helium-3 atom, the protons tend to spread apart on their repulsion, forming a linear arrangement on the opposite sides of the neutron, as illustrated in Fig. 2B. This layout makes helium-3 more susceptible to London dispersions. At the same temperature, the electron clouds in helium-3 elongate more than in helium-4. This makes the London dispersion forces between helium-3 molecules stronger than between helium-4 molecules. Therefore, the attraction between helium-3 molecules may not disappear until a much lower temperature.

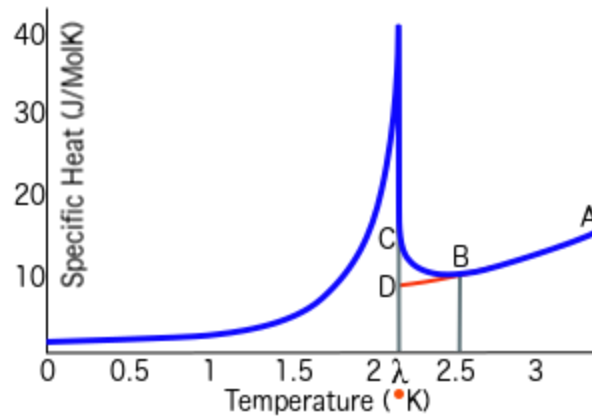
### **Transition Starting Point**

Every phase transition has a starting and an ending point, which may or may not be at the same temperature. In the case of a water-ice transition, for instance, it is normally at the same temperature. The helium-4 superfluid transition is also assumed to be at the same temperature called the  $\lambda$ -point. The following analyses will prove that this assumption is wrong.

In experiments, the end of a helium superfluid transition is visually signaled by the abrupt cease of boiling. The boiling bubbles indicate the existence of intermolecular attractions because the attractions are required to produce the surface tension for air chambers to enclose the helium vapors in the formation of the bubbles. After the transition, London dispersions no longer occur. Without London dispersion forces, the helium has no surface tension to form bubbles.

In liquid helium, heat is transported through convection and bubbling like in other liquids. After the disappearance of the bubbles, the heat transfer is continued through convection, but in a different mode: instead of regular viscous circulation, the convection becomes a direct flow of individual molecules (13). The switch of the heat transfer modality also indicates the disappearance of intermolecular attractions and viscosity.

The end of the transition is also indicated by a spike in specific heat. Fig. 3 shows the specific heat capacity of liquid helium-4 at saturated vapor pressure as a function of the temperature (14). The blue curve of the specific heat has a jump discontinuity at 2.17°K, shaped like the Greek letter lambda and therefore named the  $\lambda$ -point.



**Fig. 3. Identifying the beginning of helium-4 superfluid transitions.** The blue  $\lambda$ -shaped curve shows the specific heat vs temperature of helium-4 at saturated vapor pressure. Superfluid phenomena are observable at temperatures below 2.17°K, the  $\lambda$ -point. The significant difference between the two sides near the  $\lambda$ -point indicates superfluids have higher specific heat than liquid helium. Without any superfluid in the system to the right of the  $\lambda$ -point, the curve should follow a similar downward trend from A to B then D. However, the actual specific heat curves upwards from B to C. The higher specific heat above the red trendline may be caused by newly converted superfluid molecules. The superfluid transition could begin at point B with a temperature around 2.55°K where London dispersions are so weak that the associated liquid molecules start to break apart into individual superfluid molecules.

Thus, the end of helium-4 superfluid transition at the  $\lambda$ -point is well evidenced by the disappearance of vapor bubbles, the switch of convection modality, and the spike in specific heat. Do the transitions also start at the same temperature? This is a question to be addressed next.

A discontinuity in specific heat-temperature curves at phase transitions is not unique to helium. Water, for instance, also shows a discontinuity at water-ice transition. During the transition, both water and ice coexist. Even though the temperature may stay the same, the internal heat/enthalpy of the system may vary in a certain range. Increasing the internal heat only causes more ice to melt. The heat energy is mostly consumed to break the hydrogen bonds between the molecules in ice, and vice versa. Likewise, both liquid helium and superfluid should also coexist during a superfluid transition. As heat is removed from the liquid, the electrons in the molecules retreat to lower orbitals, weakening the London dispersions. At some point, the London dispersions will be so weak that the molecules associated with the London dispersion forces are broken apart into individual superfluid molecules.

The total energy of a system can be defined as the sum of potential energy and kinetic energy. The potential energy of the system is the sum of the potential energy of individual molecules and potential energy between molecules. The potential energy of each molecule is determined by the height of its electron cloud. The higher the cloud, the more potential energy. As electrons

retreat to lower orbitals, the potential energy radiates in the form of heat measured as temperature. Specific heat is the amount of energy influx required to increase the temperature per unit mass. The energy is primarily consumed to lift electrons to higher orbitals to increase potential energy, plus some kinetic energy as a side effect of the electron orbital transition (15). This understanding is critical to interpreting helium-4 specific heat curves.

If the superfluid transition were at the same temperature as the  $\lambda$ -point, there would not be any superfluid in the system to the right of the  $\lambda$ -point. With the homogenous liquid helium right of the  $\lambda$ -point, the specific heat should follow a similar downward curvature, trending from A to B and D, as illustrated in Fig. 3. However, the actual curve does not follow the downward trend. Instead, it curves upwards from B to C. The higher specific heat above the trendline B-D suggests that there are some changes of material in the system at least from point B. The new material must have a higher specific heat than liquid helium.

The significant difference between the two sides near the  $\lambda$ -point suggests that superfluids have a higher specific heat than liquid helium. The physics behind this observation is not fully understood. One explanation is that more energy is required to resist nuclear attractions in the effort to lift the lower orbiting electrons in superfluid molecules. Another suggestion is that it takes less energy to lift electrons that are in dispersed orbitals of molecules in liquid helium.

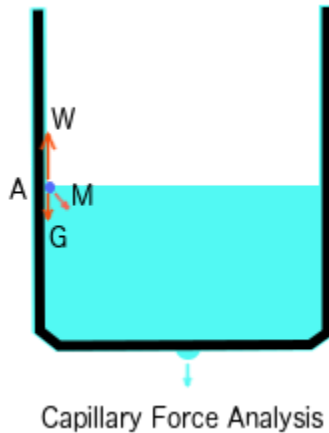
Nevertheless, these observations are sufficient for the author to postulate that superfluid molecules appear earlier than the  $\lambda$ -point and at least from point B, or the b-point for the beginning of transitions. The observed higher specific heat above the red trendline is likely the result of newly converted superfluid molecules from liquid helium as a result of the weakened London dispersions.

As more heat is removed from the system, the number of superfluid molecules increases toward the  $\lambda$ -point along with the further reduction of London dispersions. As superfluid molecules accumulate, the specific heat should increase further. The increasing upward curvature of the specific heat indicates the accelerating speed of superfluid conversion approaching the  $\lambda$ -point. If heat is removed from the system at a constant rate, the time taken to reduce the temperature should lengthen as the temperature approaches the  $\lambda$ -point, which is confirmed in experiments.

With both of the starting and ending transition point identified, the specific heat of helium-4 can be divided into three temperature sections: the liquid section with temperatures greater than the b-point where the specific heat is determined by liquid helium; the superfluid section with temperatures less than the  $\lambda$ -point where the specific heat is determined by superfluid; and the transition section with temperatures between the b-point and the  $\lambda$ -point where both superfluid and liquid helium coexist, and the specific heat is related to the ratio of the superfluid to liquid helium in the system. The transition temperature ranges from around 2.55°K to 2.17°K. This might be the range where the reduced viscosity is measured, which accounts for the two-fluid model proposed in the literature.

## Defying Gravity

One of the interesting observations in helium superfluids is that helium can creep over the rim of its container against gravity as illustrated in Fig. 4. To understand the physics behind this phenomenon, let's analyze the forces exerted at an individual molecule. Assume a helium molecule near the wall inside the container at location A. It is affected by three forces: upward adhesion to nearby molecules of the container ( $W$ ), downward gravity of the molecule weight, minus the buoyancy if it is in the fluid, ( $G$ ), and cohesion with surrounding helium molecules inside the container ( $M$ ). In liquid helium, cohesion  $M$  is a result of London dispersions. In superfluids, the London dispersions are negligible, and the cohesion will reduce to zero ( $M=0$ ).



**Fig. 4. Creeping effect of superfluids.** This is a phenomenon in which superfluids defy gravity by creeping over the wall of the container. A helium molecule at location A inside the container is pulled upwards by adhesion to the container ( $W$ ). It is also dragged downwards by gravity ( $G$ ) and cohesion with neighboring helium molecules ( $M$ ). In superfluids, the cohesion force becomes zero because the London dispersions are negligible ( $M=0$ ). Without cohesion, the superfluid molecules are pulled up along the container wall because  $W$  is a result of electromagnetic force and much stronger than gravity.

Even though there is no cohesion between superfluid molecules, adhesion may still exist between the superfluid and its container. In the case of a container made of glass, or silicon dioxide  $\text{SiO}_2$ , the oxygen and silicon atoms are held together by covalent bonds. The resulting uneven distribution of electrons in silicon dioxide produces local variations in its electrical field. The positive regions of the field create adhesion to superfluid molecules.  $W$  is the adhesion due to this type of interaction.

The electromagnetic force is vastly stronger than gravity. Without cohesion in the superfluid, the net force pulls the molecule up along the container wall. In this manner, a thin film of the superfluid molecules covers the entire surface of the container. However, the intermolecular force is only effective at a short distance. When the helium film becomes too thick, gravity pulls



the excess superfluid down along the container wall and drips off the bottom of the container as illustrated in Fig. 4.

The creeping effect is not unique to superfluids. This phenomenon can still occur if  $M$  is very small. As long as the net force of  $W$ ,  $G$  and  $M$  is upward, liquid molecules will be pulled up. Similar creeping phenomena are observed in alcohol and petroleum. This is also the same reason water level curves up along the edge of its container. Adhesion pulls the water molecules upwards. However, the molecules may not climb up too high because they are also dragged downwards by cohesion with surrounding water molecules. When a thin tube is dipped into water, the water inside the tube may be pulled up by adhesion significantly above the water level, known as capillarity. This is because the number of neighboring water molecules is limited in the horizontal direction by the diameter of the tube, resulting in less downward cohesion. Thus, superfluid creeping and capillary effects originate from the same mechanism.

### **Superleak Phenomenon**

A superleak is a phenomenon in which superfluids can flow through nanoporous membranes but regular fluids cannot. The diameter of nanoporous membrane pores is about 0.7nm, which is roughly three times the diameter of liquid helium molecules. Due to adhesion between superfluid molecules and membranes, a layer of superfluid molecules sticks on the entire surface of the membranes, reducing the size of the pores. The effective diameter of the pores is only around the size of liquid molecules. Since the electrons of superfluid molecules occupy lower orbitals, the size of superfluid molecules is smaller than liquid molecules as illustrated in Fig. 1. Hence, individual molecules of superfluids can flow through the membranes freely.

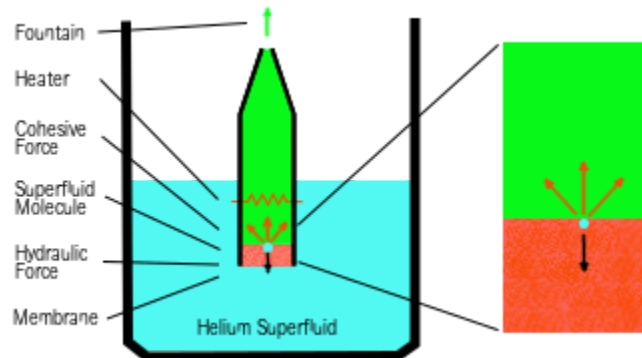
Because of cohesion between the molecules in liquid helium, additional helium molecules attach to the initial layer on the surface of the membrane. This increases the thickness of the helium layer and further reduces the size of the pores, and the pores are effectively filled and blocked by these molecules. Thus, liquid helium cannot flow through nanoporous membranes.

It has also been observed that the flow speed of superleaks decreases as the temperature increases. The flow rate of fluids is affected by viscosity and adhesivity. In relative motions, the molecules are dragged by their neighbors, creating a resistance to the flow. The lower flow rate at high temperatures is due to the presence of liquid helium in the superfluids. Decreasing the temperature reduces the proportion of sticky, liquid molecules, minimizing the resistance and leading to a faster flow rate. Increasing the temperature decreases and eventually stops the flow. As discussed earlier, helium-4 superfluid transition ranges from 2.55°K to 2.17°K during which both liquid helium and superfluid coexist. The decreased flow rate may be observed within this range.

### **Fountain Effect**

Another interesting phenomenon of superfluids is the fountain effect. A tube with a nanoporous membrane plug at one end is suspended in a bath of helium superfluid. The superfluid can flow

into the tube through the membrane. When heated, the helium flows up through the tube and squirts like a fountain as shown in Fig. 5. What's the mechanism driving this fountain?



**Fig. 5. Fountain effect of superfluids.** A superleak is created with a nanoporous membrane at the bottom of a tube. A superfluid molecule is represented by a blue dot near the top of a pore in the membrane. The heat from above turns it into a liquid molecule and subject to cohesion with the liquid above. Without a downward attraction from the superfluid below, cohesion pulls the blue molecule out of the pore like a pump. As more molecules are pumped into the tube, a hydraulic head builds up inside the tube and works against the pumping effect. As long as the tube is not too tall, the upward cohesion overpowers the downward hydraulic pressure enough to jet the liquid out the tube at the top, creating the fountain effect.

The superfluid is free to flow in the tube through the membrane, and the fluid level will be balanced in and out of the tube. When heated inside the tube, the superfluid turns into liquid helium. London dispersions create cohesion between the molecules, and they can no longer flow through the membrane. The membrane works like a one-direction check valve that only allows the superfluid to flow into the tube. However, by itself, this effect is insufficient to drive the fountain.

To understand the other half of the fountain effect, let's assume a superfluid molecule in a pore near the top of the membrane as indicated by the blue dot in Fig. 5. When the superfluid inside of the tube is heated and turned into liquid helium, cohesion is introduced between the molecules. Meanwhile, the blue superfluid molecule also absorbs heat from above. It quickly transitions into a liquid molecule and experiences cohesion with the heated molecules above. Without a downward cohesion from the superfluid below, the upward cohesion pulls the blue molecule out of the pore. The next superfluid molecule under the blue one fills the vacancy immediately, and the process repeats. As more helium enters the tube, a hydraulic head is built up inside the tube, creating a downward force on the blue molecule and resisting the upward cohesion. However, the upward cohesion is electromagnetic in origin and stronger than the downward hydraulic force. As long as the tube is not too tall, the hydraulic force cannot prevent helium from being jetted out the tube at the top, creating the fountain effect.

## Predictions

The proposed theory has thus far been useful for understanding and explaining the existing observations of superfluid phenomena. However, the fundamental point of a theory is to provide novel predictions, which not only help us plan for the future but also allow us to disprove flawed theories. Next, let's discuss some more abnormal phenomena predicted by this theory.

First, it would be interesting to study the relationship between the viscosity of helium and temperature. Viscosity in most liquids normally increases with the decreasing temperature. However, the proposed theory predicts otherwise for helium. The viscosity-temperature curve for helium-4 should be different in the three sections around the  $\lambda$ -point. As the temperature decreases, the viscosity should increase like other liquids in the liquid section to the maximum at the  $\lambda$ -point, then decrease in the transition section to zero at the  $\lambda$ -point, and remain zero in the superfluid section.

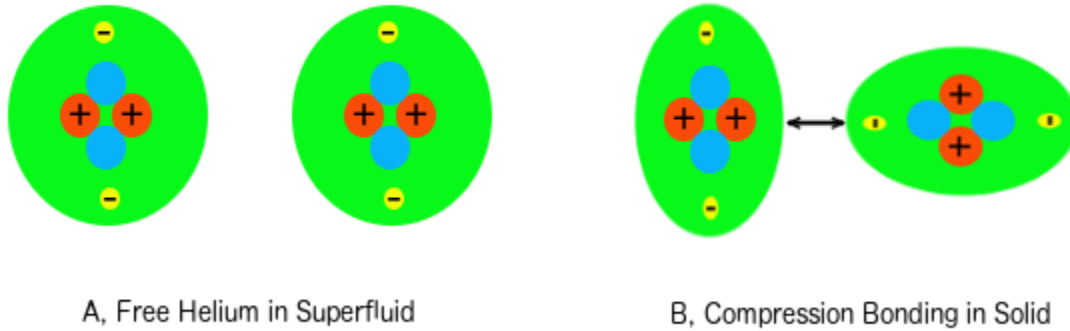
Second, in the absence of gravity, water molecules will assemble to form droplets due to cohesion. However, this behavior should not be expected for superfluids. When superfluids are spilled in a gravity-free environment, there will not be any droplet formation. Instead, individual molecules will disperse into space. It might seem as if the superfluid had evaporated, but no phase change has occurred. It only appears as such due to the lack of cohesion between superfluid molecules to hold them together.

Another prediction about helium superfluids is that the helium will never solidify at regular pressures, even at 0°K. Since there are no attractions between molecules in superfluids, the molecules cannot stick together to form solids regardless of the temperature. Superfluids appear liquid simply because the molecules are pulled down by gravity and collected at the bottom of their container. This is distinctly different from molecules of liquid helium which are held together by cohesion.

Nevertheless, at high pressures (>2.5MPa) and low temperatures (1-1.5°K), solid helium-4 has been obtained (16, 17). At regular pressures, liquid helium would have turned into superfluid at those temperatures. In general, interparticle attractions are required for any viscous fluid. Without the attractions, the fluid is superfluid. Interparticle attractions are also necessary for any solid. Without the attractions, there is no solid but "fine powder" of molecules. To be able to resist shear stresses, the molecules in solids must be held together by some form of bonding between them. Since there is no cohesion between superfluid molecules, simply packing the molecules together would not create solids that can resist shear stresses. So how can higher pressure cause the helium to form solids?

Our answer to the last question is a prediction of a novel type of bonding holding the molecules together in solid helium. At high pressures, helium molecules are squeezed together. In response to the repulsions of the electrical fields from surrounding molecules, the electron cloud of each molecule shrinks along the axis of the two protons. The uneven distribution of electron density in different directions creates local variations in the electrical field: positive on the axis of

the protons and negative on the plane perpendicular to that axis. An attraction arises from the fields between molecules. Let's call it compression bonding. Driven by this force, the molecules reorient themselves to minimize the potential energy between them. Eventually, the system will stabilize at a low potential layout between molecules as shown in Fig. 6B.



**Fig. 6. Formation of compression bonding.** Under regular pressures, superfluids can be obtained from liquid helium by reducing the temperature. Solid helium cannot be produced by further decreasing the temperature because there are no attractions to hold the molecules together. Under high pressures, the electron cloud of each molecule shrinks along the axis of the two protons. The uneven distribution of the electron density in different directions creates local variations in its electrical field. An attraction arises from the fields between the molecules: namely compression bonding. Solid helium is formed by molecules held together by this new type of bonding.

Fig. 6B shows the smallest chain of two molecules held together by this bond. Various larger chains may be extended from this basic block to all the directions in 3D space, creating amorphous structures with low densities. As pressure increases, the chains may be squashed into a more compact layout where the unit structure is formed by four molecules bonded together by compression bonding in a rotationally symmetric structure. Helium crystals with higher densities may be obtained in such a compacted structure.

Solid helium has also been obtained at room temperatures, but under much higher pressures, greater than 11.5GPa (18). Under such high pressures, helium molecules are compressed so tightly that London dispersions are disrupted and replaced by compression bonds. There may be a period during the transition when the net force between molecules switches from attractive to repulsive before the formation of compression bonds. Superfluids could appear as the net force crosses zero. However, such superfluids are likely unstable. A minor perturbation in pressure or temperature may trigger changes of phase, which somewhat resembles supercritical fluids.

Compression bonding might also exist in solids of other elements. Under pressures of around 400GPa, hydrogen becomes metallic (19, 20). The regular covalent bonds between hydrogen atoms may be disrupted and replaced by the compression bonds at such high pressures, converting the hydrogen from diatomic to metallic.

Lastly, this theory also predicts the existence of superfluids inside neutron stars. The force between neutrons is repulsive. Without any attraction between the particles, superfluids should be the most common form of matter in neutron stars.

Many other predictions could be made with this theory based on the principle that superfluids are collections of particles without attractions between them. For the sake of brevity, we will not list them all here but leave it for curious readers to fill the rest of the list.

### Conclusions

Normal fluid is composed of cohesive particles, whereas superfluid is a collection of individual particles without cohesion. The unique properties of superfluids are caused by the absence of interparticle attractions. The attraction between helium molecules can be eliminated primarily due to its unique atomic structure: the combination of small atomic size and even distribution of electrons. Intermolecular attractions are always present between molecules with uneven electron distribution. Molecules with an even distribution of electrons are rare, which explains superfluids are so scarce. The proposed theory advanced our knowledge at the microscopic level, which helped us better understand the information revealed in helium specific heat and allowed us to identify the starting point of its superfluid transition. Now, it is clear that helium-4 transitions not at a single temperature but in a range from around 2.55°K to 2.17°K; the  $\lambda$ -point just marks the end of the transition. The two-fluid phenomenon and the superleak speed variation may be observed in the transition phase where both superfluid and liquid helium coexist. The theory also predicts that superfluids never solidify at regular pressures, even at 0°K. Finally, it further suggests the existence of compression bonding that is responsible for holding molecules together in solid helium. Even though this theory agrees with all the observations in superfluids, its validity may be further tested by its predictions.

### Acknowledgment

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