Press Release

Keio University

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4-dimensional phase transition actually exists
─Superfluid phase transition of helium in nanoporous materials─

A research group comprising doctoral student Tomoyuki Tani (at the time of research), at the Keio University Graduate School of Science and Technology, School of Fundamental Science and Technology, Professor Keiya Shirahama, and research associate Yusuke Nago, at the Keio University Faculty of Science and Technology, Department of Physics, found that liquid helium confined in a nanoporous glass, a material with nanometer-sized sponge-like pores, undergoes superfluid phase transition(*1) of 4-dimensional XY type. This means that although it is spatially 3-dimensional, a substance that exhibits 4-dimensional phase transition has actually been found.

Phase transitions are classified into categories called "universality class"(*2), and ordinary liquid helium belongs to the 3-dimensional XY universality class. It is also known that thin helium films exhibit a 2-dimensional XY Berezinskii-Kosterlitz-Thouless (BKT) superfluid transition. From previous studies, it was known that helium in nanoporous materials exhibit 4-dimensional XY quantum phase transition at absolute zero. The present study showed for the first time that superfluid transition at finite (non-zero) temperatures is also 4-dimensional. Theoretically, 4-dimensional phase transition provides the simplest example of the phase transitions, and its experimental discovery will make significant contributions to our understanding of phase transition phenomena.

The outcomes of this research were published in the Journal of the Physical Society of Japan in March 2021. It was selected as an Editor's Choice paper by the same journal and was also featured on their English website JPS Hot Topics.

1. Main Points of Research

- Discovery that helium confined in sponge-like nanopores undergoes a superfluid phase transition of 4-dimensional XY type.
- Interpreted to be the appearance at finite (non-zero) temperature of a 4-dimensional quantum phase transition composed of "3 spatial dimensions plus 1 imaginary time dimension."
- The 4-dimensional phase transition is the most fundamental of the phase transitions, but it was difficult to realize in actual materials. There is great significance in its realization and it will likely contribute to our understanding of phase transition phenomena.

2. Background of Research

Changes in states of matter, such as when water turns into ice, is called "phase transitions." Phase transitions not only occur in substances familiar to us, but also play an important role in, for example, the creation of the universe and elementary particles. Phase transitions were actively studied in the second half of the 20th century as an important topic in physics, and a fundamental understanding was established through "renormalization theory."

An important characteristic of phase transition is that the mechanism of transition greatly depends on the dimension of the substance. Ordinary substances are 3-dimensional, in which atoms and molecules extend in all directions in space. On the other hand, atomically thin film substances can be considered as 2-dimensional. Even if the material is the same, a 2-dimensional phase transition can occur through a completely different mechanism to that of 3 dimensions. Furthermore, problems of phase transitions can be solved in 2 or 1 dimensions, although 3-dimensional phase transition is difficult to consider theoretically. Thus, spatial dimensionality plays an important role in phase transition. Surprisingly, in many phase transitions, theory becomes simplest when a "4-dimensional" spatial dimension is hypothetically considered. If a 4-dimensional phase transition actually exists, it will provide the most fundamental framework for understanding phase transition.

Superfluid phase transition of liquid helium has been studied in great detail and has made important contributions toward our understanding of phase transitions. Helium is a refrigerant indispensable when using superconducting magnets such as in medical MRIs. At very low temperatures of around 2 kelvins (-271 ℃) or lower, it undergoes a phase transition to the superfluid state, in which liquid helium loses its viscosity. When a phase transition occurs, physical quantities such as specific heat diverge. It is called critical phenomena, which are described by sets of the critical exponents. One can classifies the phase transition into a category called "universality class" from the values of critical exponents. The superfluid phase transition of helium belongs to the 3-dimensional XY universality class. On the other hand, thin helium films adsorbed onto a solid surface is known to be a 2-dimensional substance and exhibits a "2-dimensional XY" BKT superfluid phase transition. BKT phase transition is also called a "topological phase transition," and it is well known that J. M. Kosterlitz and D. J. Thouless who proposed this were awarded the 2016 Nobel Prize in Physics.

3. Content of Research and Results

In this study, a detailed investigation was carried out into the superfluid phase transition of liquid helium when it is confined in a nanoporous glass. Porous glass has numerous tiny nanometer-sized holes like a sponge. By measuring the flow of helium in the nanopores, the critical exponent of a physical quantity called superfluid density was accurately measured. It was found that the critical exponent at various pressures all had a value of 1. This exponent 1 is different from the value of 0.67 (two-thirds) that is expected for the 3-dimensional XY class, but is that of 4-dimensional XY. In other words, when helium is confined into a nanometer-sized sponge, a 4-dimensional phase transition is realized, a quite peculiar outcome.

Why does the 4-dimensional phase transition takes place in the nanoporous material? In a previous study conducted by this research group, helium in the nanoporous glass exhibited a "quantum phase transition." While an ordinary phase transition is caused by thermal fluctuations, quantum phase transition is caused by "quantum fluctuations" that exist even at absolute zero. When helium is confined in a nanoporous material and pressure is applied, a quantum phase transition where superfluidity gradually disappears takes place. This quantum phase transition can be explained theoretically by considering a further dimension in the imaginary time in addition to the fluctuations in the 3 spatial dimensions (figure 1). The 4-dimensional quantum phase transition of "3 spatial dimensions plus 1 imaginary time dimension" takes place at absolute zero. However, the present study shows that this 4-dimensional phase transition also occurs at finite temperatures that is not absolute zero. As shown in figure 1, in confined helium, many nanoscale superfluid droplets called "localized Bose-Einstein condensates (LBECs)" exist even at temperatures higher than the superfluid transition temperature. Each LBEC has the size of the "correlation length" (green circles in the figure) and has a quantum mechanical phase (its direction is shown by the arrows). At high temperatures (figure 1, top), the phase fluctuates randomly in both the 3-dimensional space and imaginary time directions, and the helium shows no superfluidity despite of the emergence of LBECs. This study has revealed that phase fluctuations are caused not only by thermal effect but also by quantum mechanical uncertainty of confined helium. Very close to the transition temperature (figure 1, bottom), the correlation length increases in all directions of the 4 dimensions, the LBECs overlap, and the phases align in a given direction, resulting in a superfluid state.

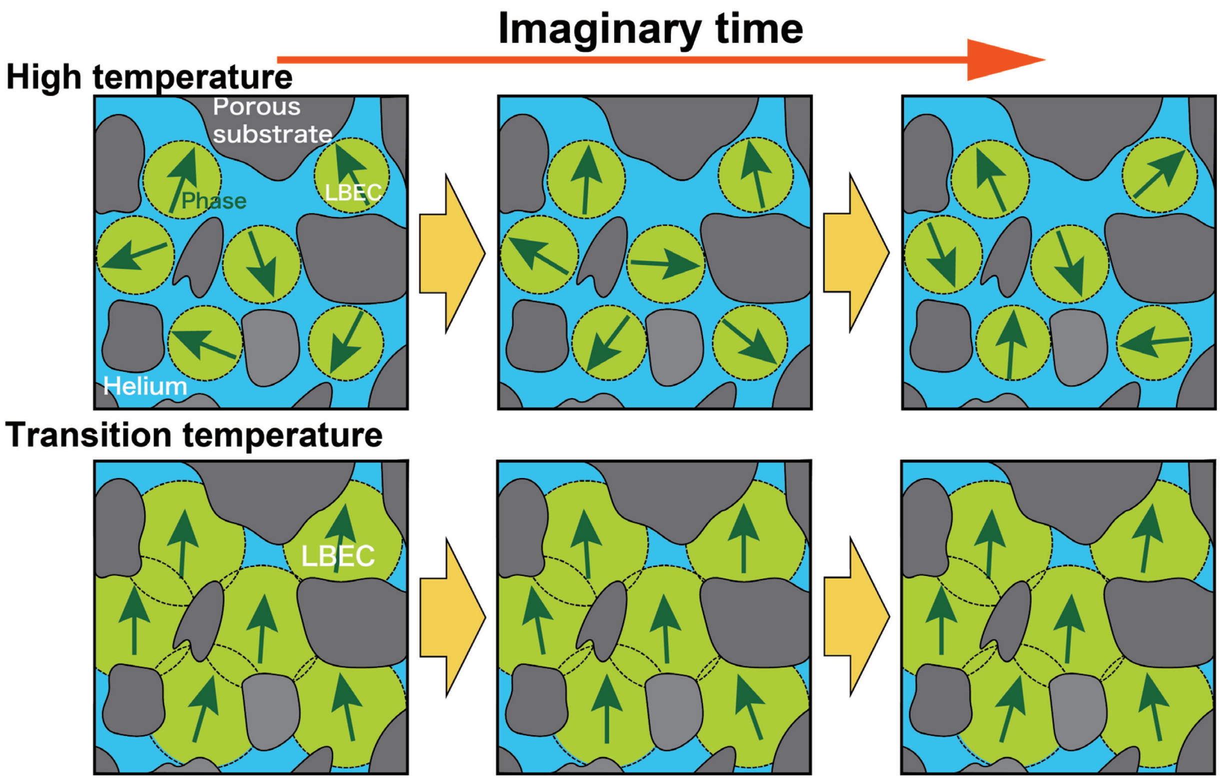

Figure 1. 4-dimensional phase transition of helium in nanoporous materials. Liquid helium (blue) enters the nanopores of porous material (gray). At around 2 kelvins or lower, there are many "LBECs" (green) with quantum mechanical phases (indicated by the arrows). At high temperatures (top), the direction of the phase fluctuates not only in the 3-dimensional space but also in the "imaginary time dimension," which is determined by the inverse temperature, and the helium shows no superfluidity. As the transition temperature is approached (bottom), the phases between the LBECs become aligned and superfluidity occurs, but phase correlation also exists in the imaginary time dimension, resulting in a 4-dimensional phase transition.

4. Future Developments

Theoretically, 4-dimensional phase transition is the simplest example of the phase transitions, but it had been difficult to realize in actual substances. In this study, it was found that helium in nanoporous materials exhibits 4-dimensional phase transition. One may expect that helium in nanoporous media contributes toward the understanding of phase transition and topological quantum phenomena.

<Details of Journal Article>

Evidence for 4D XY Quantum Criticality in ^{4}He Confined in Nanoporous Media at Finite Temperatures
Tomoyuki Tani, Yusuke Nago, Satoshi Murakawa, and Keiya Shirahama
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<Glossary>

*1 Superfluid phase transition

Liquid helium undergoes a phase transition at around 2 kelvins, entering a nonviscous superfluid state. Among the phase transition phenomena, superfluid phase transition has been studied in the greatest detail and is a classic example of second-order phase transition.

*2 Universality class
In second-order phase transitions, "matters show critical phenomena," in which physical quantities such as specific heat and magnetic susceptibility diverge at the transition temperature. Even in different phase transitions in different substances, for example magnetic transitions in solids and superfluid transition in helium, the critical phenomena are characterized by the common critical exponents, if the structures and spatial dimensions of the "order parameter" describing the order are the same, a phenomenon called "universality." That is, the critical phenomena belong to the same universality class. Superfluid transition belongs to the XY universality class, similar to "XY magnets," in which the magnetic moment can only move in the 2-dimensinal, i.e. XY, plane.

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