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Torsional oscillator experiment on superfluid $^4$He confined in a porous alumina nanopore array

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Abstract. We studied superfluidity of liquid $^4$He confined in an array of well-characterized straight nanopores of porous alumina (PA). The PA plate sample of 45 nm pore size is set in an annular flow channel and the superflow is detected by torsional oscillator (TO) technique. Superfluid transition $T_c$ in the nanopores is suppressed by 3.5 mK from the bulk $\lambda$ point. $T_c$ is consistent with the temperature at which the healing length is equal to the pore radius. We have observed many anti-crossing anomalies in the TO frequency associated with dissipation peaks, which are attributed to the coupling to second sound resonances.

Superfluid $^4$He confined in nanoporous materials has been attracting renewed interests. Recent studies show that superfluidity of $^4$He confined in a nanoporous glass (with pore size $d = 2.5$ nm) is strongly suppressed and $T_c$ approaches 0 K at a critical pressure [1, 2]. This behavior is understood as a quantum phase transition (QPT). Moreover, we have shown by a heat capacity study that the QPT occurs by the emergence of the so-called localized Bose-Einstein condensation (LBEC) state, in which the macroscopic phase coherence is lost between many nanoscale condensates by the confinement of $^4$He to nanopores.

Interestingly, the suppression of superfluidity by nanoscale confinement is never explained by the traditional concept of the superfluid healing length $\xi$, in which $T_c$ is determined by the condition $\xi \sim d$, because $\xi$ of superfluid $^4$He is about 0.3 nm, much smaller than the pore size. The anomalous superfluid suppression is interesting not only theoretically [3, 4], but also in realizing a true superfluid Josephson junction (JJ). Josephson effect in superfluid $^4$He has been observed only in the very vicinity of the $\lambda$ point $T_\lambda$, where $\xi$ becomes comparable to the size of the currently available apertures[5].

We aim at developing a novel Josephson device working at arbitrary temperature based on the superfluid suppression in the nanopores. To realize a well defined JJ, a plate that has an array of nanopores whose axes direct normal to the surface has to be prepared. We employ porous alumina (PA) as such a device. PA is produced by anodic oxidation of aluminum plate. By optimizing the oxidation condition, a triangular array of straight nanopores with a uniform pore size can be formed. Since the pore size of PA is typically 10 $\sim$ 100 nm, PA itself is not appropriate for the $^4$He JJ. However, one can decrease the pore size at the end of the pores by depositing other materials such as gold. As a preliminary study, we have fabricated and characterized PA, and examined superfluid properties of $^4$He in a PA plate.

The PA plate having nanopores boring through the plate is prepared as follows: An Al plate is...
anodized in an oxalic acid. Figure 1 (a) shows a SEM image of the PA. We optimize the condition so as to form a regular honeycomb array of straight nanopores as seen in the photograph. The pore diameter is estimated to be 45 nm and the distance between the pores is 100 nm. Since the nanopores in PA terminate at the opposite side to the oxidized planes, the remaining Al and alumina at the pore ends are removed by a phosphoric acid. By this final procedure all the nanopores pierce through the plate. The final thickness of the PA plate is $165 \ \mu m$.

We have examined superfluidity of $^4$He by a torsional oscillator (TO). Figure 1 (b) shows the cross section of the oscillator. The oscillator bob contains an annular conduit of $1.5 \times 1.0 \ mm^2$ cross sectional area. The perimeter of the conduit is about 50 mm. The conduit is filled with bulk liquid He and acts as an ”AC” flow channel when the bob oscillates around the torsion axis. The PA plate is inserted in the channel so that the axis of nanopores is perpendicular to the flow. This setup was adopted from flow experiments of superfluid $^3$He [6, 7]. Unlike the ordinary TO technique in which the superfluid fraction is related to the change in period, the response of the present TO does not correspond to the superfluid component, but to the superflow inside the nanopores. Since the viscous penetration length of liquid $^4$He is much larger than the pore size, the normal $^4$He liquid inside the PA plate block perfectly the flow of the bulk liquid in the channel. The moment of inertia of the bulk liquid entirely contribute to the resonant frequency of TO. Below the superfluid transition temperature $T_c$ of liquid inside the pores (not at bulk $T_c$), the superfluid component can flow in the nanopores. The flow velocity field is determined so that the circulation along the annular channel (through one of the nanopores) is quantized, i.e. zero. The resonant frequency of the TO should show a step-like increase just below $T_c$ due to the occurrence of ”AC” superflow in the nanopores and the bulk channel.

The torsional oscillator is mounted on a dilution refrigerator. In order to stabilize the temperature around 2 K, it in fact acts as a $^4$He cryostat by thermally connecting the 1 K pot to the TO. Temperature was calibrated at the superfluid transition temperature of bulk $^4$He. The resonant frequency $f$ is about 1170 Hz and $Q$ of the resonance is about $8 \times 10^4$ at low temperature. The TO is operated using a feedback circuit with a constant driving voltage (force). In the present study, pressure of $^4$He liquid is set at 0.1 MPa.

Figure 2 shows the shift in frequency from the value at $T_\lambda$, $\Delta f(T) \equiv f(T) - f(2.17K)$ and dissipation $Q^{-1}$ derived from the amplitude of the TO. As $T$ decreases, $f$ increases abruptly at 2.17 K, then many anti-crossing resonances appear accompanied with sharp dissipation peak. At the lowest temperature (1.67 K), the difference of $\Delta f$ reaches about 1 Hz. The magnitude of $\Delta f$ is consistent with the frequency shift that is estimated from the abovementioned condition, in which all the superfluid in the annulus apparently decouple from the oscillation.

The response of TO reflects more clearly the superfluid properties by looking at a blowup of $\Delta f(T)$ near $T_\lambda$ shown in Fig. 3. The temperature is plotted as $\Delta T \equiv T - T_\lambda$. The frequency decreases with decreasing temperature above $T_\lambda$, and shows a sharp minimum at $T_\lambda$, then abruptly increases at temperature 3.5 mK below $T_\lambda$, which is denoted as $T_c$. The small, positive
Δf between \( T_\lambda \) and \( T_c \) is most probably due to the potential flow of superfluid component with a boundary condition of the annulus with a partition of PA and normal fluid. Since \( \Delta f \) immediately reaches about 0.7 Hz just below \( T_c \), it is clear that the superflow occurs inside the nanopores keeping with the quantized circulation condition along the perimeter of the annulus. Therefore, \( T_c \) is firmly identified to be the superfluid transition temperature inside the nanopores.

The healing (coherence) length \( \xi \) at \( T_c \) is estimated to be 23 nm, which is exactly equal to the pore radius. Therefore, the suppression of superfluidity in the present nanopores is understood well as the effect of suppression the superfluid order parameter near the pore wall, which has been theoretically formalized as the \( \Psi \) theory [8–10]. Smaller pore size is obviously needed to realize our idea of the JJ by the large superfluid suppression.

Below \( T_c \), a sequence of anomalies is seen in the temperature sweep measurements. The semi-log plot of Fig. 4 clearly shows more than fourteen anti-crossing resonances in \( \Delta f \) accompanying with absorption peak seen in \( Q^{-1} \). These anomalies are attributed to the excitation of second sound resonances by torsional oscillation. It is well known that oscillating superleak can excite second sound [11]. Since the present pore size is much smaller than the viscous penetration length for normal component at all temperatures, the PA plate works as an excellent superleak.

In the annulus channel, the second sound standing waves of wavelength \( \lambda = 2L/n \), where \( L \) is the perimeter of the annulus and \( n \) is an integer. It is easily inferred that each of many anti-crossing anomalies may correspond to one of the standing waves. Moreover, most of the anomalies are located at rather high temperatures \( 2K < T < T_\lambda \). This is understood that the second sound velocity greatly depends on temperature in this regime.

Most interestingly, there are two different types of anomalies, which can be assigned to ”large” and ”small” resonances from their strengths of the signals. They emerge alternately. We speculate that the large and small modes are standing waves with odd and even \( n \), respectively. In our annulus TO setup, the ”ends” of the second sound resonators are regarded as ”connected”; i.e. the front and back of the single PA plate act as two transducers. Suppose that the superleak
moves to the right: On the right side of the superleak, the normal fluid density $\rho_n$ increases whereas the superfluid density $\rho_s$ decreases, while on the left side, $\rho_n$ decreases and $\rho_s$ increases.

In this situation, the standing waves must have anti-nodes whose phase are opposite on the front and the back of the PA plate, and hence $n$ is odd. Since such waves can easily be excited, larger anomalies are assigned to be this odd – $n$ resonances.

Since the smaller anomalies are located between the larger ones, they can be assigned to be even – $n$ standing waves. In the even – $n$ standing waves, the phases of the two anti-nodes on both PA surfaces are same. The same phase can be realized if the superleak generates heat from viscosity of the normal component. From the data of second sound velocity [12], we assign the anomalies from $n = 6$ to 19.

In conclusion, we have made a porous alumina plate with an array of nanopores of 45 nm in diameter, and have carried out torsional oscillator measurements for confined liquid $^4$He. The suppression of $T_c$ at 0.1 MPa is 3.5 mK, which comes up to expectation from previous studies. Smaller pore size is needed for realizing the Josephson junction. We attempt to contract the pores by depositing other materials such as gold or carbon on porous alumina.

We have observed a number of anti-crossing resonances due to the coupling of second sound standing waves and torsional oscillation. Torsional oscillator can be an excellent tool for superfluid studies employing second sound.

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