Cw-NMR study of Liquid $^3$He in Nanometer-sized Porous Alumina

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Abstract. Continuous-wave NMR measurements were performed for liquid $^3$He in porous alumina discs, which have many small pores of 200 nm in nominal diameter regularly aligned in the same direction. The experimental cell is composed of a stack of 85 anopore discs with C-shaped disc spacers between them. The spacers make the sample space well defined and make it easier to discriminate between liquid NMR signals from different spaces. To eliminate solid $^3$He layer adsorbed on the alumina’s surface, 4 atomic layers of $^4$He were pre-coated on the surface in the experimental cell. Experiments were made at pressure of 17.9 bar and temperatures down to about 0.5 mK. The obtained NMR signals are composed of two contributions below superfluid transition temperatures. One seems to come from the liquid inside pores and the other between each anopore discs.

1. Introduction
Superfluid $^3$He confined in narrow-size geometry has attracted much interests because superfluidity should be drastically affected by the geometrical size comparable to the coherence length. Since the coherence length of superfluid $^3$He at 0 K varies from about 90 to 18 nm depending on the pressure from 0 to 34 bar [1], the nanometer size pore is comparable to the coherence length and suitable for investigating the size effect for superfluid $^3$He.

Recently we have started the continuous-wave NMR study for investigating superfluidity of $^3$He in porous alumina with many small pores [2]. The porous alumina used here is the Anopore that is a product of Whatman Inc. Anopore is provided in the form of Anodisc membrane filter, which is composed of an alumina matrix manufactured electrochemically. The honeycomb pore structure provides a narrow pore size distribution and the pore directions are well aligned each other. The discs used here is 13 mm in diameter and 60 $\mu$m in thick, having nominal pore size of 100 nm. According to the Whatman Inc, however, the actual structure of 100 nm Anodiscs is composed of long 200 nm pore (57 $\mu$m in depth) with very thin layer of 100 nm pore (3 $\mu$m). Since the layer of 100 nm pore is negligibly small, we will discuss the present results as the nature in 200 nm pores.

2. Experiment
Figure 1 shows a schematic view of the cell and experimental set-up. The experimental cell is composed of a stack of 85 Anodiscs with C-shaped spacers between them. These spacers are
Figure 1. (Color online) A schematic view of cw-NMR cell

made of UPILEX [3] with 12.5 \( \mu \)m in thickness, making the sample space outside pores well defined. The thickness of the spacer is larger than the coherence length so that liquid \(^3\)He in this space is considered as bulk liquid. The NMR frequency shift due to superfluid transition should be quite sensitive to an angle between the applied magnetic field and the wall, or a size of the space, we should be able to distinguish the observed signals if superfluid transition occurs.

85 Anopore membranes and spacers are put into a sample chamber (6 mm in height) made of machinable glass ceramic (Macor [4]). The sample chamber is connected through a narrow channel (1 mm in diameter) to a sintered powder heat exchanger, the mixture of Ag and Pt powder with a surface area of about 62.16 m\(^2\), to make a good thermal contact with the copper nuclear stage. The temperature is measured with a \(^3\)He melting curve thermometer (MCT) and a Pt NMR thermometer, which are mounted near by the sample tower in the low field experimental region. NMR measurements were made with a continuous wave method at a frequency of 639 kHz. A static field of 19.7 mT was applied in parallel to the pores and swept to cover the whole absorption line. A saddle type rf coil wound around the sample chamber produces an rf field perpendicular to the pores. The rf field was small enough to avoid the saturation of \(^3\)He spin system. The \(^4\)He coverage was prepared with the following procedure. \(^4\)He gas was introduced at 4.2 K while monitoring the isothermal adsorption pressure by using a room-temperature pressure gauge. Preferentially adsorbed \(^4\)He was annealed for several hours at 4.2 K. To avoid \(^4\)He desorption, \(^3\)He gas was liquefied slowly at temperatures below 100 mK. The introduced \(^4\)He gas corresponds to 4 layers of \(^4\)He (total \(^4\)He density of 39.8 nm\(^{-2}\)), if we use 12.2 nm\(^{-2}\) and 9.2 nm\(^{-2}\) as the maximum \(^4\)He areal density for the first layer and the upper layers on alumina.
3. Results and discussion

Figure 2 shows NMR spectra for 17.9 bar at various temperatures in the warming process, where the horizontal axis is given as frequency shift from the Lamor Frequency (639 kHz). The numbers written in the figure are the temperature normalized by $T'_c = 2.126$ mK. The spectra show a positive frequency shift below $T/T'_c = 1.0$ and a small satellite peak appears with a smaller frequency shift compared with the main one below $T/T'_c = 0.95$. Surprisingly, there is no Larmor signal at the lowest temperature, suggesting that all liquid $^3$He enters into a superfluid phase in spite of the fact that the pore size in the alumina is comparable with the coherence length.

The magnetization obtained from numerical integration of the absorption lines shows large reduction for the main peak at lower temperatures, indicating that the main peak originates from bulk liquid between the Anodiscs and corresponds to superfluid $B$ phase below $T/T'_c = 1.0$. $T'_c$ is consistent with the transition temperature $T_c = 2.16$ mK for bulk liquid within experimental error. The satellite peak appears below $T/T'_c = 0.95$ with small suppression, suggesting that it comes from the narrow pores. Furthermore, the magnetization calculated for the satellite peak
is almost constant below the transition temperature, which is characteristic for the superfluid A phase. This is consistent with our assumption that A phase must be more stabilized in the narrow pores.

Quantitative understanding for temperature dependence of frequency shift or magnetization is currently underway. The frequency shift for the main peak is finite, but smaller than longitudinal resonant frequency $\Omega_B$ [5], suggesting the $n$ vector is slightly tilted from the direction of magnetic field $H_0$. On the other hand, in order to understand the frequency shift for the satellite peak, we should take account of several complicated effects such as the suppression of the superfluid gap, the spatial dependence of gap and the texture effect in very narrow pores, etc.

4. Conclusion
We have carried out cw-NMR measurements for liquid $^3$He in porous alumina with well aligned pores of 200 nm in nominal diameter, which is comparable to the coherence length of superfluid $^3$He. Liquid $^3$He in 200 nm pores seems to have superfluid phase similar to bulk A phase.

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