Effect of the cooling speed through $T_c$ on the formation of textures in superfluid $^3\text{He-A}$

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Abstract. The cw-NMR measurements have been performed for superfluid $^3\text{He}$ A-phase in a single cylinder with $115 \, \mu\text{m}$ inner radius. We observed two peaks in NMR spectra, the main peak and the satellite peak. The satellite peak is attributed to textures which are induced by the flow due to temperature gradient by controlling the cooling speed of samples from normal fluid state to superfluid A-phase. We have observed that the satellite peak height of NMR spectrum increases continuously as the cooling speed increases. The number of possible texture types is restricted for our cylindrical cell, since the radius of the cell is about ten times larger than the dipole coherence length $\xi_D \sim 10 \, \mu\text{m}$. Therefore, it is unlikely that the continuous change of NMR spectrum is attributed to the different kinds of textures. We discuss that these results are due to textural domain structure along cylindrical axis.

1. Introduction

The superfluid $^3\text{He}$ A-phase confined in restricted geometries has been extensively studied [1, 2, 3, 4]. Since its energy gap is anisotropic, the orbital part of the order parameter $l$ must be perpendicular to the walls. The spin part of the order parameter $d$ is directed by a large magnetic field $H$ ($\gg \sim 3 \, \text{mT}$) to be $d \perp H$. In a bulk geometry, $l$ prefers to be parallel to $d$ due to the dipole-dipole interaction, and forms the uniform dipole-locked texture. In restricted geometries, on the other hand, a texture is determined by the competition of above orientational effects. In the case of a narrow cylinder with the radius being about ten times of the dipole coherence length $\xi_D \sim 10 \, \mu\text{m}$, a few types of texture are expected, the Mermin-Ho, the Pan-Am, and the Radial Disgyration texture [3, 5].

Earlier measurements in the cylindrical geometry of $100 \, \mu\text{m}$ inner radius tubes discovered three types of textures depending on the condition of cooling through $T_c$ [3]. But they were not conclusive to decide the texture under various cooling conditions because of the possibility of various textures in each 150 tubes. For further understanding of the texture in the cylindrical geometry, we made a cylinder cell with a single $115 \, \mu\text{m}$ inner radius polyimide tube.

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2. Experiments

Our cylindrical cell consists of a single polyimide tube with 115 µm inner radius and 36 mm length. Upper and lower ends of the tube are connected to two disk-shaped bulk spaces. These two disk-shaped spaces are additionally connected to each other through a tube of 1 mm radius to eliminate a temperature gradient between two spaces. The lower disk-shaped space is connected to a heat exchanger mounted on a nuclear demagnetization stage. All the parts excluding the 115 µm radius tube are made of Stycast 1266.

The cw-NMR measurement was performed at 700 kHz under a static magnetic field, \( H = 21.6 \, \text{mT} \), applied parallel to the axis of the tube. A NMR pick-up coil is located at the height of 11 mm from the lower end of the tube. The form of the pick-up coil is approximately rectangular saddle. Its height is about 4 mm along the tube axis. Therefore, our NMR measurement detects liquid \(^3\text{He}\) in the region of 115 µm radius and about 4 mm length. The sample pressure was 3.2 MPa and the temperature was measured with a melting curve thermometer located outside of the sample on the nuclear demagnetization stage. The superfluid transition temperature of our sample was about 2.44 mK.

3. Results

To study the effect of the cooling speed through the superfluid transition \( T_c \) on the NMR measurements, we have controlled several cooling speeds from the normal phase, 1.05 \( T_c \), to the A-phase, 0.90 \( T_c \), then cooled sample down to 0.80 \( T_c \) at about 1 µK/min. A static magnetic field (\( H = 21.6 \, \text{mT} \)) was applied during the whole processes. NMR spectra at 0.80 \( T_c \) are shown in Fig. 1 for various cooling speed through \( T_c \). The main peak height of NMR spectrum decreases continuously as the cooling speed increases. At the same time, a satellite peak appears at around \( \Delta f = +3 \, \text{kHz} \) from the Larmor frequency and then increases its peak height. Each shape of NMR spectrum does not change even with much faster cooling speed below 0.9 \( T_c \). This result indicates that only a temperature sweep near \( T_c \) is important to these changes of the spectra. Those spectra were so stable to be observed for a day when the sample was left at rest.

![Figure 1. NMR spectrum at 0.80 \( T_c \) for various cooling speeds through \( T_c \), from 0.14 µK/min. to 9.2 µK/min. A satellite peak appears at around \( \Delta f = +3 \, \text{kHz} \) from the Larmor frequency and its intensity increases as the cooling speed increases.](image)

The satellite peak is attributed to "texture". The number of possible types of textures is
limited in our cylindrical cell because of a strong boundary condition for \( l \), to be perpendicular to the wall and the radius of our cell is about ten times larger than the dipole coherence length. In addition, \( d \) is almost perpendicular to the cylindrical axis due to a large magnetic field along the axis. Therefore, it is unlikely that the observed changes of NMR spectrum is attributed to the change among the different kinds of textures. We identify this texture as Type C texture in Ref. [3], which was observed with rapid cooling under no rotation. We considered that these NMR spectra were due to textural domain structure grown along the cylindrical axis and such domain structures were created by the flow. In this experiment, we are able to change the speed of flow induced by temperature gradient along the axis by controlling the cooling speed of samples from normal fluid state to superfluid A-phase. As mentioned above, that the rapid cooling causes the large satellite signal means that the axial flow during superfluid transition might be effective to create more textural domains along the axis. A similar change of domains by controlling the conditions of cooling through \( T_c \) was also observed in a slab geometry [7].

![Figure 2](image2.png)

**Figure 2.** Proportion of satellite signal intensity in the total signal intensity at 0.80 \( T_c \) for various cooling speeds through \( T_c \). The proportion of satellite signal is saturated above 4 \( \mu \)K/min.

![Figure 3](image3.png)

**Figure 3.** Frequency shift of satellite peak normalized by main peak shift at 0.80 \( T_c \) for various cooling speeds through \( T_c \). A small change of position of satellite peak was observed below 3 \( \mu \)K/min.

The proportion of satellite signal intensity in the total signal intensity is shown in Fig. 2 as a function of cooling speed through \( T_c \). The satellite signal intensity was evaluated by fitting NMR spectra with double Lorentzian curves. The proportion of satellite signal is saturated above around 4 \( \mu \)K/min. Figure 3 shows normalized frequency shift of satellite peak, \( R_t^2 \) as a function of cooling speed through \( T_c \). \( R_t^2 \) is defined as follows;

\[
\Delta f = R_t^2 \frac{f_A^2}{2f_L} \tag{1}
\]

where \( \Delta f \) is a frequency shift of satellite peak from Larmor frequency, \( f_A \) is the longitudinal frequency shift in A phase, and \( f_L \) is the Larmor frequency. Our \( R_t^2 \) is almost the same as transverse satellite frequency of twist solitons (Fig. 3 in Ref. [8]). Therefore our domain walls might consist of that twist solitons. A small decrease of \( R_t^2 \) of satellite peak was observed below about 3 \( \mu \)K/min. as the cooling speed increases (Fig. 3).
Below about 3 µK/min., the satellite signal intensity become larger and $Rt^2$ become smaller as the cooling speed increases. These changes seems to correspond to increase of soliton distance described in Ref. [8]. Above about 4 µK/min., the satellite signal intensity and $Rt^2$ are almost constant. So it is thought that the textural domains are not created any more.

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References
[1] Hakonen P J and Nummila K K 1987 Jpn. J. Appl. Phys. 26 Suppl. 26-3-1 181
[2] Hakonen P J, Nummila K K, Simola J T, Skrbek L and Manniashvili G 1987 Phys. Rev. Lett. 58 678
[3] Ishiguro R, Ishikawa O, Yamashita M, Sasaki Y, Fukuda K, Kubota M, Ishimoto H, Packard R E, Takagi T, Ohmi T and Mizusaki T 2004 Phys. Rev. Lett. 93 125301
[4] Yamashita M, Izumina K, Matsubara A, Sasaki Y, Ishikawa O, Takagi T, Kubota M and Mizusaki T 2008 Phys. Rev. Lett. 101 025302
[5] Vollhardt D and Wolfe P 1990 The Superfluid Phases of Helium 3 (London: Taylor & Francis) chapter 7 pp 288-292
[6] Kubota M, Obara T, Ishiguro R, Yamashita M, Igarashi T, Hayata E, Ishikawa O, Sasaki Y, Mikhin N, Fukuda M, Kovacik V and Mizusaki T 2003 Physica B 329 1577
[7] Walmsley P M, White I J and Golov A I 2004 Phys. Rev. Lett. 93 195301
[8] Bruinsma R and Maki K 1979 Phys. Rev. B 20 984