Available online at www.sciencedirect.com
SCIENCE DIRECT
Physica B 329–333 (2003) 66–67
PHYSICA B
www.elsevier.com/locate/physb

Vortex nucleation and texture of rotating ^{3}He-A in cylindrical cells with $R \simeq 10\xi_D$

R. Ishiguro[a,*], M. Yamashita[a], T. Igarashi[b], E. Hayata[a], O. Ishikawa[c], Y. Sasaki[a], K. Fukuda[e], M. Kubota[b], H. Ishimoto[b], T. Mizusaki[a], T. Ohmi[a], T. Takagi[d], R.E. Packard[f]

[a] Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
[b] Institute for Solid State Physics, University of Tokyo, Chiba 277-8581, Japan
[c] Graduate School of Science, Osaka City University, Osaka 558-8585, Japan
[d] Department of Applied Physics, Fukui University, Fukui 910-8507, Japan
[e] College of Medical Technology, Kyoto University, Kyoto 606-8507, Japan
[f] Department of Physics, University of California, Berkeley, CA 94720, USA

Abstract

We measured cw-NMR at 700 kHz for rotating ^{3}He-A at 31.5 bar confined in two sizes of cylinders with 0.1 and 0.2 mm diameters at rotation speeds up to 6.28 rad/s. The NMR signals varied for the different size cylinders. Nucleation of the single vortex was observed in the 0.2 mm cylinder above a critical rotational speed and hysteresis appeared for vortex nucleation and annihilation when the rotational speed was changed. On the other hand in 0.1 mm cylinder, a vortex did not appear up to 6.28 rad/s, and the NMR absorption gradually changed as the rotation speed increased.

Keywords: Superfluid ^{3}He-A; NMR; Texture; Vortex

We studied rotating superfluid ^{3}He-A in cylindrical sample cells under rotation. This work is an extension of the previous experiment [1] but was carried out under higher rotation speed up to 6.28 rad/s in sub mK temperature range, and by using the improved cw-NMR.

We prepared two cylindrical cells with 0.1 and 0.2 mm diameters which were about 10 times larger than the dipole coherence length $\xi_D \sim 10$ μm and about 150 cylindrical samples were put together in each cell and their cylinder axis was parallel to the rotation axis and also parallel to the magnetic field.

We observed (1) three kinds of NMR satellite signals in the 0.1 mm diameter sample cell which came from localized spin waves in textures and (2) one kind of textural satellite signal and a doubly-quantized non-singular vortex signal in 0.2 mm diameter sample cell. There was no vortex nucleation observed in the 0.1 mm diameter cell up to 6.28 rad/s. In this report we present the results on nucleation and annihilation of a single vortex in the 0.2 mm diameter sample cell.

Fig. 1 shows a typical NMR absorption spectrum observed for 0.2 mm sample at $T/T_c = 0.75$ where the dotted line is the cw-NMR adsorption spectrum at rest and the solid one is the spectrum at 6.28 rad/s. The spectrum is characterized by a parameter R_t^2 defined by $\Delta f = R_t^2 (f_L^A)^2 / 2f_0$, where Δf is the frequency shift from the Larmor frequency f_0 and f_L^A is the temperature dependent longitudinal frequency in the A phase.

The characteristic feature of the spectrum at rest is that there is a peak at $R_t^2 = 1$ and the absorption spectrum continuously extended toward f_0 due to the texture. The solid line taken under 6.28 rad/s has 2 peaks. The main peak is located at $R_t^2 = 1$ and the

*Corresponding author.
E-mail address: ishiguro@scphys.kyoto-u.ac.jp (R. Ishiguro).

0921-4526/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0921-4526(02)01883-5

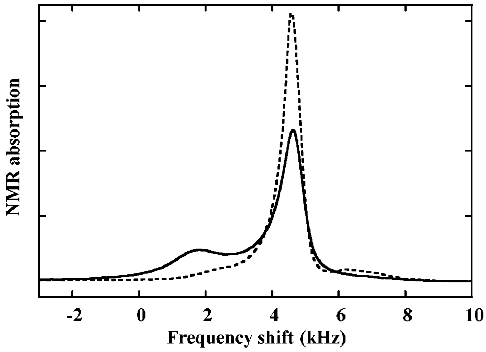

Fig. 1. NMR absorption line shapes for the 0.2 mm sample at $T/T_c = 0.75$ as a function of frequency shift from Larmor frequency. The dotted line is shown at rest, and the solid line is shown when the cryostat rotates at 6.28 rad/s.

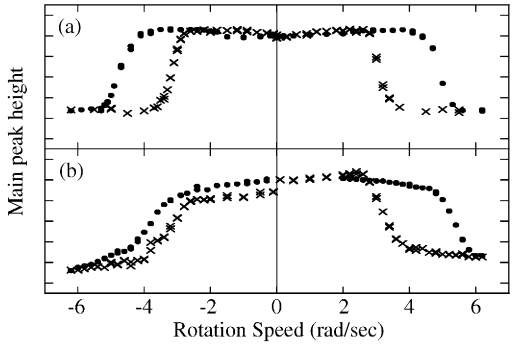

Fig. 2. NMR absorption at $R_t^2 = 1$ during acceleration (solid circle) and deceleration (cross). (a) The sample was cooled to superfluid at rest and (b) it was cooled under the rotation speed of +2 rad/s.

satellite peak is located at $R_t^2 \sim 0.37$. The main peak comes from the texture, which is the same as the solid line. The satellite peak appeared at a certain critical rotation speed when we increased the speed and it disappeared at a different critical rotation speed when we reduced the speed from the vortex state. The value of $R_t^2 \sim 0.37$ is very close to the doubly quantized non-singular vortex which are observed in bulk ^{3}He-A [2].

Fig. 2 shows the change in NMR absorption signal as a function of the rotation speed Ω. Since the main peak height is most sensitive to the change of the texture, the main peak height is plotted against rotation speed. Solid circles were taken as the speed increased and the crosses when the speed decreased. Data in Fig. 2(a) were taken when the sample was cooled to superfluid state at rest and data in (b) when the sample was cooled to the superfluid state under a rotation speed of +2 rad/s. In Fig. 2(a), data of solid circles change rapidly around $\Omega_{c1} = 5.0$ rad/s and data of crosses changes rapidly at Ω_{c2} (~ 3.5 rad/s). Data are rather symmetric for both directions of rotation. It was found that the sudden change in the main peak height corresponded to sudden change in the satellite absorption and was caused by the textural change due to introduction of a single vortex in the cell. In Fig. 2(b), data for a positive rotation are not symmetric against negative rotation. This asymmetry can be attributed to the textural memory effect [3] at the onset of superfluidity.

This nucleation and annihilation phenomena can be interpreted as the same mechanism applied for the ^{4}He case [4]. The edges of our cylindrical cells were connected with the bulk liquid, and when there were no vortex in the 0.2 mm sample cell, there were many vortices in the bulk. For this reason, in order to nucleate the vortex in 0.2 mm cell, it is not needed to exceed a critical velocity v_c which makes the texture unstable. The nucleation and annihilation of the vortex in a cylindrical cell are determined as follows: The free energy $E'(r) = E(r) - \Omega L$ under a rotation Ω can be calculated as a function of the position of the vortex r from the center of the cylindrical cell. The vortex nucleation occurs when the free energy $E'(r)$ at the center $r = 0$ becomes negative above a certain rotation speed Ω_{c1}. The critical angular velocity Ω_{c1} is calculated by vortex line approximation, and is given by $\Omega_{c1} = n\kappa/(2\pi R^2)\ln(R/a)$, where n is the quantum number of circulation 2, κ is the circulation, R is the radius of the cylinder and a is roughly the vortex core radius $\simeq \xi_D$ (10 μm). For 0.2 mm cell, Ω_{c1} becomes 4.8 rad/s. When the rotation speed is above Ω_{c2}, $E'(r)$ is the minimum at $r = 0$ and the maximum in $E'(r)$ exists somewhere between $r = 0$ and R. When rotation speed is below $\Omega_{c2} = n\kappa/(2\pi R^2)$, the energy barrier disappears. For 0.2 mm cell, Ω_{c2} becomes 2.0 rad/s. Therefore, the nucleation of the vortex is caused by introduction of the pre-existing vortices in bulk sample into the cylindrical cell and the annihilation of the vortex is due to disappearance of the energy barrier in $E'(r)$ at Ω_{c2}.

Agreement of the calculation with experiment is good. The texture and the large core size of the texture should be considered in the calculation to explain the textural memory effect and to get better agreement with experiment.

This joint research was carried out at ISSP, University of Tokyo.

References

[1] O. Ishikawa, et al., Physica B 284–288 (2000) 248.
[2] O.V. Lounasmaa, E. Thuneberg, Proc. Natl. Acad. Sci. USA 96 (1999) 7760.
[3] A.J. Manninen, et al., Phys. Rev. Lett. 77 (1996) 5086.
[4] R.E. Packard, et al., Phys. Rev. A 6 (1972) 799.