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<td>Author(s)</td>
<td>Ishiguro, R; Ishikawa, O; Yamashita, M; Sasaki, Y; Fukuda, K; Kubota, M; Ishimoto, H; Packard, RE; Takagi, T; Ohmi, T; Mizusaki, T</td>
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Kyoto University
Vortex Formation and Annihilation in Three Textures of Rotating Superfluid $^3$He-A


1Institute for Solid State Physics, University of Tokyo, Chiba 277-8581, Japan
2Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan
3Graduate School of Science, Osaka City University, Osaka 558-8585, Japan
4Research Center for Low Temperature and Materials Sciences, Kyoto University, Kyoto 606-8502, Japan
5College of Medical Technology, Kyoto University, Kyoto 606-8507, Japan
6Department of Physics, University of California, Berkeley, California 94720, USA
7Department of Applied Physics, Fukui University, Fukui 910-8507, Japan

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Textures, textural transformation, and formation and annihilation of a single vortex were investigated in narrow cylinders with 100 $\mu$m radius in A-phase under rotation up to 6.28 rad/sec. Three textures were found, depending on the cooling conditions of the sample through the superfluid transition temperature $T_c$. We found the gyromagnetic effect of textures; that is, two textures (A or B) could be selected either by applying a magnetic field in parallel or anti-parallel to the rotation axis. The critical angular speed of a single vortex formation $\Omega_A$ and that of annihilation $\Omega_B$ for each texture were measured. The textural transformation in type A texture was induced by rotation. Both type A and B textures held macroscopic angular momentum along the rotation axis. We identified the texture for type A, B, and C as Mermin-Ho, radial disgyration, and a soliton type of defect along the axis, respectively.

Vortices in the bulk superfluid $^3$He-A phase were studied extensively [1,2], including their nucleation and annihilation at a wall [3–5] and at the A-B phase boundary [6]. However, the behavior of a single vortex in this system was studied only recently [7]. To further our understanding of the vortex transition process, we constructed a new rotating cryostat [8] which can rotate up to 6.28 rad/sec, a speed sufficient to create a vortex in the restricted geometry of a narrow tube. This allowed us to study single vortex formation and texture transformation due to flow in a well-controlled texture.

Earlier measurements in the restricted geometry of a 0.5 mm diameter tube were not conclusive to show either texture transformations or vortex formation under rotation [9]. In a preliminary report [10], we described two types of textures, but could not control them by various cooling conditions. In this Letter, we report success in controlling the textures, thus enabling us to study what kind of A phase textures exists in narrow cylinders for various conditions of rotation, magnetic field, and cooling conditions. We can also determine how the texture influences the formation and annihilation of a vortex.

The A phase of superfluid $^3$He is described by two vectors, $\hat{I}$ is a vector specifying the orbital part of the order parameter and $\mathbf{d}$ specifies the spin part. A texture refers to the spatial distribution of both vectors in a given sample. Three types of textures have been proposed for a cylindrical geometry: the Mermin-Ho (MH), the Pan-Am (PA), and the radial disgyration (RD) [11,12]. The MH texture has a three-dimensional structure of $\hat{I}$ producing a circulation of a single quanta $\kappa_0$ ($\kappa_0 = 0.066$ mm$^2$/sec), thus holding a macroscopic angular momentum [12]. The PA texture is planar and does not give rise to macroscopic angular momentum. Finally, the RD texture may possess macroscopic angular momentum even though it has a planar structure because a single quantum of circulation can be attached to the singular core.

We have studied rotating $^3$He-A at 31.5 bars in narrow cylinders. The radius of a long narrow cylinder was 100 $\mu$m, which was about 10 times the dipole coherence length $\xi_D$. The sample cell was composed of a bundle of 150 cylinders, both sides of which were connected with bulk liquid $^3$He. The rotation vector was parallel to the cylinder’s axis. For our maximum speed of rotation $\Omega = 6.28$ rad/sec, the radius of cylinders was comparable to the spacing in a vortex lattice of doubly-quantized vortex and only a couple of vortex formation is expected.

We performed cw-NMR measurements at 700 kHz, and the NMR magnetic field of about 22 mT was applied parallel to the axis of the cylindrical sample. Regarding the NMR spectrum, vortices and textures may produce spin wave satellite peaks on the widespread background of the textural local mode spectrum. Spin waves are characterized by their normalized frequency shift $f^L$, which is related with the resonance frequency $f_0 + R^L(f_0^2 / 2f_0)$, where $f_0$ is the Larmor frequency and $f^L$ is the temperature-dependent longitudinal frequency in A phase. Roughly speaking, the spin wave satellite signal comes from the part of the texture whose spatial variation occurs in the scale of $\xi_D$, while the local mode of spectrum comes from the part which changes slowly in space.

Figure 1 shows three types of cw-NMR absorption spectra, A (dotted line), B (dashed line), and C (solid...
with the magnetic field of broadened to lower frequencies. 

The material was cooled under a rotation speed of when it was cooled under the same rotation speed with the opposite direction of the magnetic field (when it was cooled under the same rotation speed with the sample cell. These spectra look similar to each other and the large satellite signal appeared at the height of the main peak at . The satellite peak at peaked at a different critical rotation speed decreased after the vortex formation at 31 rad/sec, which flowed parallel to the sample axis. We believe that this was the texture we observed in the previous report (the dotted curve in Fig. 2 in Ref. [13]) according to the spectrum and the way of cooling through .

Figure 2 shows typical NMR absorption spectra for the type A at with increasing rotation speeds. The spectrum at is almost the same as that at (solid line). The major change of the NMR spectrum occurred only at around (dashed line), above which the height of the main peak at decreased and the satellite peak at appeared. The spectrum at 6.28 rad/sec (thick solid line) was almost the same as at . The value of occurred at and its temperature dependence was very similar to that for the doubly-quantized continuous vortex observed in bulk $^3$He-A [14]. We therefore identify this sudden change of spectrum as a formation of a single doubly-quantized vortex in the cylinder. When the rotation speed decreased after the vortex formation at , the satellite peak disappeared at a different critical rotation speed . We attributed this sudden change of spectrum to a vortex annihilation.

Similar formation and annihilation of a vortex were observed for the type B texture. The positions of the satellite peaks of the vortices for both types A and B are almost identical. We observed similar formation and annihilation of a vortex for the type C texture as well. The satellite peaks due to vortex formation also appeared at . Since the type C texture was unstable against external disturbance and vortex formation, we did not investigate it thoroughly.

Figure 3 shows the main peak height as a function of a rotation speed for type A and B. Data in Fig. 3(a) were obtained by increasing rotation speeds, and . The spin wave peak for a vortex was observed at 0.31.

![FIG. 1. NMR absorption spectra for $\Omega = 0$ at $T/T_c = 0.75$ as a function of frequency shift from the Larmor frequency. Spectra for three textures, labeled by a dotted line for A, a dashed line for B, and a solid line for C are shown. Textures were controlled by the condition of cooling through $T_c$.](image)

![FIG. 2. NMR absorption spectra for type A at $T/T_c = 0.75$ as a function of frequency shift from Larmor frequency with increasing rotation speeds, $\Omega = 0, 4.0, 4.8,$ and 6.28 rad/sec. The spin wave peak for a vortex was observed at $R_t^2 = 0.31$.](image)
taken for a sample which had been initially cooled through $T_c$ under (+2 rad/sec, −22 mT), whereas data in Fig. 3(c) were taken for a sample cooled under both rotation and field direction simultaneously inverted as (−2 rad/sec, +22 mT). Textures for Figs. 3(a) and 3(c) were identical and classified as type A. Data in Fig. 3(b) were taken for a sample cooled through $T_c$ under (+2 rad/sec, +22 mT), whereas data in Fig. 3(d) were for (−2 rad/sec, −22 mT). Textures for Figs. 3(b) and 3(d) were identical and classified as type B. The selection between types A and B was controlled by the relative direction of the magnetic field to rotation direction. Thin arrows indicate the direction of the change of rotation speed. Data were very reproducible and showed a large hysteresis curve between acceleration and deceleration of rotation speed.

As shown in Fig. 3(a), when $\Omega$ increased from $\Omega_{ini} = +2$ rad/sec, a single vortex appeared at $\Omega_f = +4.8$ rad/sec. Here the rotation speed in the middle of a transition was used as the critical rotation speed. When $\Omega$ decreased from +6.28 rad/sec as shown by solid circles, the vortex was annihilated at $\Omega_a = +3.2$ rad/sec. When $\Omega$ further decreased to $\Omega = 0$ and increased in the reversed direction, the big dip shown by the thick arrow appeared at $\Omega_d = −1.5$ rad/sec. When $\Omega$ further increased in the reversed direction, vortex formation occurred at $\Omega_f = −4.8$ rad/sec. Vortex annihilation was observed at $\Omega_a = −3.2$ rad/sec during deceleration. When $\Omega$ decreased to $\Omega = 0$ and increased in the positive direction as shown by open circles, a small dip shown by the thick arrow in the inset of Fig. 3(a) appeared at $\Omega_d = +1.5$ rad/sec. Asymmetry of the size of the dips (not the rotation speed) was also observed in Fig. 3(c), when the sample was cooled with $\Omega_{ini} = −2$ rad/sec. The big dip always appeared in the opposite direction from the initial rotation direction $\Omega_{ini}$. The transition width for both the vortex formation and annihilation was about ±0.5 rad/sec and was attributed to the distribution among the cylinders.

In Figs. 3(b) and 3(d), similar formation and annihilation of a single vortex were observed. But response of type B texture against the direction of rotation was not symmetric. The critical rotation speed for annihilation $|\Omega_a|$ was 3.2 rad/sec for both directions and was almost the same as that for type A. But the critical speed for formation $|\Omega_f|$ depended on the rotation direction. The $|\Omega_f|$ was 5.5 rad/sec for the same rotation direction as the initial rotation direction $\Omega_{ini} (= ±2$ rad/sec). However, $|\Omega_f|$ was 4.1 rad/sec for the opposite rotation direction from $\Omega_{ini}$. No dip such as those in type A was observed in type B. This asymmetry (the dips for type A and asymmetric critical speed $|\Omega_f|$ for type B) indicated the asymmetric structure of textures against rotation. Both type A and B textures should have a macroscopic angular momentum along the rotation axis.

We investigated the temperature dependence of the critical rotation speed $\Omega_f$ and $\Omega_a$. The critical speed $|\Omega_f|$ and $|\Omega_a|$ for type A, shown by solid circles and open circles in Fig. 4, did not depend on temperatures up to

FIG. 3. NMR absorption of the main peak at $R_2^*$ = 1.0 as a function of rotation speed $\Omega$ during acceleration and deceleration cycle. The conditions of cooling the sample though $T_c$ are: (a) (+2 rad/sec, −22 mT), (b) (+2 rad/sec, +22 mT), (c) (−2 rad/sec, +22 mT), (d) (−2 rad/sec, −22 mT). The spectra (a) and (c) correspond to type A texture and (b) and (d) to type B. Thin arrows indicate the direction of taking data and vertical lines are $\Omega_f$ and $\Omega_a$ for type A.

FIG. 4. The critical speed for vortex formation $\Omega_f$ shown by solid circles and annihilation $\Omega_a$ shown by open circles as a function of temperature for type A texture.
T/T_c = 0.975. The average values, |Ω_1| = 5.0 rad/sec and |
Ω_d| = 3.4 rad/sec, are shown by dotted lines. The critical rota-
tion speeds for type B, |Ω_{C1}^B| = 5.5 rad/sec, |
Ω_{C1}^F| = 4.1 rad/sec, and |Ω_d| = 3.2 rad/sec did not de-
pend on temperature as well.

When the sample was cooled through T_c with Ω_{in} =
4 rad/sec, a vortex did not appear. Thus, a vortex could not
exist in the samples for Ω < 4 rad/sec even at T_c. These
facts suggest that the observed Ω corresponds to the
critical speed Ω_{C1}, which is defined by F(r, Ω_{C1}) =
F(r) - Ω_{C1}L_v = 0 at r = 0, where F(r) is the kinetic
energy of vortex and L_v is the angular momentum of
the vortex, and r is the distance of vortex from the center.

The observed Ω_a can be understood as the critical speed
of rotation Ω_{CA} when the energy barrier for trapped
metastable vortex disappears [10,15,16]. These values,
Ω_{C1} and Ω_{CA}, are temperature independent and are com-
parable to the observed values of Ω_1 and Ω_d, even though
we neglected the textural effect [10].

Here we qualitatively discuss the textural effect on
Ω_1. If a texture has an angular momentum, L_v, the free
energy under rotation changes to F(Ω) = F - ΩL_v - ΩL_v.
Since L_v has the same direction as Ω, the last term is
always negative. However, since the sign of L_v depends on
the direction of textural angular momentum, the second
term changes its sign, depending on the direction of Ω.
Thus, a nonzero value of L_v causes the asymmetric re-
sponse against rotation. The MH texture, MH(±), has a
macroscopic angular momentum L_v with a circulation
n = ±1 in the unit of k_0 [12]. The RD texture, RD(±),
has a singularity at the center, and the circulation of this
texture can be n = ±1 if it is created under a sufficiently
high rotation speed. As we have explained earlier, both
types A and B texture have a macroscopic angular mo-
momentum, which exclude the possibility of PA texture.

We would explain our results in Fig. 3 by identifying
type A as MH(±) and type B as RD(±) as follows. For the
MH(+) texture in Fig. 3(a), the textural transformation to
MH(−) occurs at the dips when a soft core vortex with
n = −2 is introduced to the cylindrical sample at Ω_d =
−1.5 rad/sec and then two soft cores merge with each other.
When the rotation speed increased further in the same
direction, a soft core vortex with n = −2 is intro-
duced at Ω_f = −4.8 rad/sec and the total circulation
becomes n = −3. During the deceleration of Ω, a vortex
with n = −2 disappears at Ω_d = −3.2 rad/sec. And then,
another textural transformation from MH(−) to
MH(+) occurs at the dip of Ω_d = +1.5 rad/sec. When
Ω further increases, a soft core vortex with n = +2 is
introduced at Ω_f = +4.8 rad/sec. Therefore, even
though MH texture has a macroscopic angular momentum,
the critical velocity of vortex nucleation is symmet-
ric for both rotation directions. This scenario was
confirmed by our numerical calculation of the stability
of texture with a soft core vortex in cylinder under
rotation and will be published elsewhere. We do not
know why the depth of the dips is not symmetric for
rotation. It should be noted that the spectrum shown in
Fig. 2a of Ref. [10] was taken for a sample cooled through
T_c without rotation. The textures in this case were con-
sidered to be mixtures of MH(+) and MH(−), hence we
did not observe clear dips at ±1.5 rad/sec. For the
RD(+) texture in Fig. 3(b), it is unlikely that the singular
vortex core of the RD texture can be merged with a soft
core vortex with n = −2. Therefore, the RD texture does
not transform, even though a soft core vortex is intro-
duced at Ω_f or Ω_d. Thus, a vortex formation becomes
asymmetric for rotation due to a fixed circulation with
n = ±1.

We have investigated the vortex formation in well-
controlled textures in a cylinder. It was surprising that
the textures could be controlled by the relative direction
between the magnetic field and rotation when the sample
was cooled through T_c. This is a kind of gyromagnetic
effect and further theoretical studies are needed.

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