NMR Experiments on Rotating Superfluid ^{3}He-A: Evidence for Vorticity

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(Received 7 December 1981)

Experiments on rotating superfluid ^{3}He-A in an open cylindrical geometry show a change in the NMR line shape as a result of rotation: The amplitude of the peak decreases in proportion to $f(T)g(\Omega)$, where Ω is the angular velocity of rotation; at the same time the line broadens. Near T_c, $f(T)$ is a linear function of $1-T/T_c$. At small velocities $g(\Omega) \propto \Omega$. These observations are consistent with the existence of vortices in rotating ^{3}He-A.

PACS numbers: 67.50.Fi, 76.60.-k

The "super" superfluid ^{3}He-A has a number of unique properties which have been studied since 1972. Some of the most interesting phenomena should, however, show up only under rotation; various vortex structures are expected to appear and result in solid bodylike rotation of the superfluid component.[1-3] In ^{3}He-A it is possible to have singular vortex structures, as well as two-dimensional vortex arrays which do not show any singularities in the distribution of the order parameter. In the latter case the superfluid circulation around the elementary cell boundaries of the vortex lattice is described by even multiples, 2 or 4, of the circulation quantum $h/2m_3$, where $2m_3$ is the mass of the Cooper pair. A singular vortex array may exist with circulation $h/2m_3$.

The energies of the singular and nonsingular structures are of the same order of magnitude although they are distinct; in equilibrium only one may exist at a time. For example, in a strong magnetic field, $H \gg H_c = 25$ Oe, the singular state should be the equilibrium configuration. However, because of the different times needed to generate the various vortex structures and because of the inevitable metastability anticipated from topological considerations,[4] even the energetically less favorable structures should be observable.

In this Letter we report our first experiments on rotating ^{3}He-A. We studied texture changes due to rotation in a cylindrical vessel in an axial magnetic field with NMR techniques. Vortices were expected to change the NMR line,[3] but the effect was assumed to be small, increasing slowly with Ω, the angular velocity of rotation. We found, however, astonishingly large and regular changes in the NMR spectra as a function of Ω. This regularity strongly suggests the existence of vortices in rotating ^{3}He-A.

Our experiments were performed in a rotating nuclear demagnetization cryostat, the "ROTA MINILAB".[5] Usually the ^{3}He sample was cooled at rest deep to the inside of the A phase. During the ensuing warmup the cryostat was successively rotated and stopped while the NMR spectra were recorded. In some of our experiments the ^{3}He sample was cooled to the A phase while rotating.

Our experimental cell is a long ($L = 30$ mm) and narrow (diam $= 5$ mm) cylinder. The pressure of ^{3}He in the cell was 29.4 bars. The temperature was measured by a pulsed platinum NMR thermometer,[6] calibrated at T_c. The angular velocity range was 0.28–0.84 rad/s. The speed of rotation was constant within ± 2.5% during one revolution. The warmup rate of the cryostat was kept small, usually at a few microkelvins per minute, to avoid large temperature gradients across the cell. A change of the warming rate from less than 1 μK/min to 10 μK/min had no effect on our results.

The cw method was employed for measuring the transverse NMR absorption signal at the fixed frequency of 920 kHz. This corresponds to a magnetic field of 284 Oe, which was swept back and forth over the resonance. Three different field homogeneities were used over the 2-cm length, viz., 3.7×10^{-5}, 8.5×10^{-5}, and 2.7×10^{-4}, which were deduced from the normal Fermi liquid NMR linewidths $\Gamma_H = 34$, 78, and 244 Hz, respectively. In the last case, the intrinsic line-

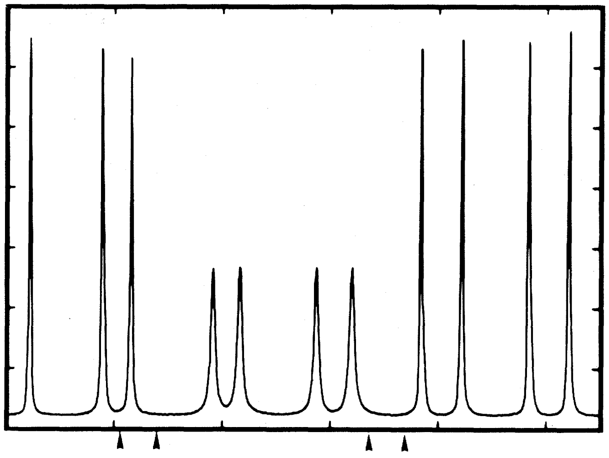

FIG. 1. A sequence of NMR absorption peaks as a function of time: t_1, start rotation; t_2, final velocity reached; t_3, stop the motor; t_4, cryostat stops. The field homogeneity was 3.7×10^{-5}, $\Omega=0.84$ rad/s, and $1-T/T_c=0.152$. Each division on the horizontal axis is 1 min.

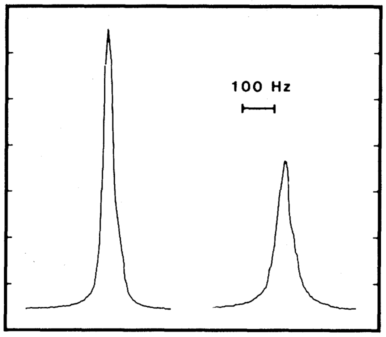

FIG. 2. NMR absorption line shapes as a function of frequency at the highest field homogeneity 3.7×10^{-5}. The frequency increases to the right. The first peak was obtained with the cryostat at rest and the second at $\Omega=0.63$ rad/s. The reduced temperature $1-T/T_c=0.127$.

width $\Gamma(T)\ll\Gamma_H$ at all temperatures. In ^{3}He-A $\Gamma(T)\propto1-T/T_c$ and, consequently, at higher homogeneities $\Gamma(T)\ll\Gamma_H$ only near T_c; at lower temperatures $\Gamma(T)$ approaches Γ_H.

Figure 1 illustrates a sequence of NMR peaks measured in an experiment during which rotation was started and stopped at intervals of a few minutes. The data show that the changes in the NMR peak develop much more rapidly than the acceleration and deceleration time of the cryostat.

The integrated total absorption at rest and during rotation remains the same within our accuracy of about 3%. The frequency range of integration was 10 to 20 times the linewidth. The reason for the reduction in the peak height during rotation is an additional line broadening Γ_Ω, as illustrated in Fig. 2. Our measurements show that rotation broadens the bulk A-phase peak on both sides; the broadening on the low-frequency side is larger.

Instead of directly measuring Γ_Ω, it is experimentally more accurate to study the change in the peak height, $\Delta I=I-I_\Omega$, where I is the peak amplitude at rest and I_Ω is the amplitude measured in rotation. ΔI was investigated as a function of Ω, T, and the homogeneity of the magnetic field. At low temperatures the relative change in the peak height, $\Delta I/I$, was almost independent of T. Consequently, $\Delta I/I$ could be measured as a function of Ω accurately in this temperature range. The results with our best homogeneity are shown in Fig. 3. At small angular velocities, $\Delta I/I$ is a linear function of Ω. At higher angular velocities $\Delta I/I$ starts to saturate, as one might expect.

We studied the temperature dependence of $\Delta I/I$ at rotation speeds roughly in the linear region of Fig. 3. $\Delta I/I$ was found to be proportional to the magnetic field homogeneity near T_c. This led us to plot the dimensionless quantity $(\Delta I/I)(2\pi/\Omega)\Gamma_H$ as a function of temperature, the normal liquid linewidth Γ_H being a parameter (Fig. 4). All the curves show the same linear dependence on $1-T/T_c$ near T_c. In the case $\Gamma_H=244$ Hz, the linear region extends to $1-T/T_c\cong0.09$; at higher-field homogeneities the linear temperature dependence

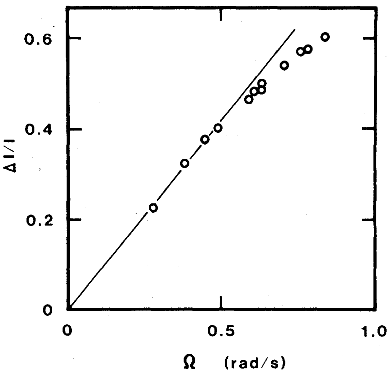

FIG. 3. The change in the normalized NMR peak amplitude plotted as a function of the angular velocity. The measurements were made at our highest homogeneity, 3.7×10^{-5}.

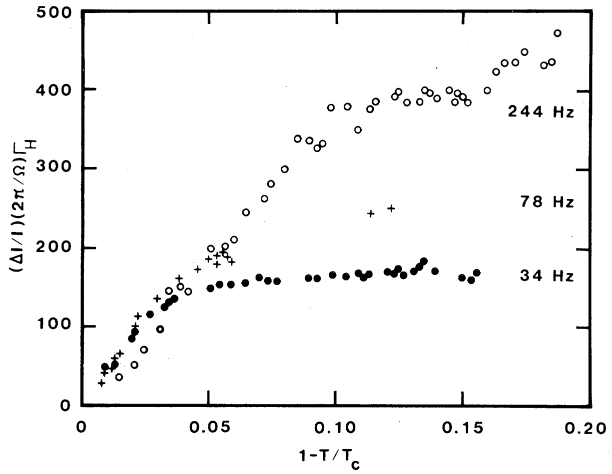

FIG. 4. The change of the normalized NMR peak amplitude as a function of the normalized temperature at three different magnetic field homogeneities, corresponding to $\Gamma_H = 34$, 78, and 244 Hz, respectively.

is valid for a shorter interval in $1-T/T_c$. This seems to be related to the narrowing of the region where $\Gamma(T) \ll \Gamma_H$.

Consequently, we find that near T_c

$$(\Delta I/I)\Gamma_H(2\pi/\Omega)(1-T/T_c)^{-1} = \text{const} \qquad (1)$$

and that this quantity does not depend on Γ_H, Ω, or on $1-T/T_c$. In this temperature region $\Gamma(T)$ as well as Γ_Ω are small compared with Γ_H. The amplitude I is determined by the inhomogeneity of the field, viz., $I \propto 1/\Gamma_H$. One may conclude from Eq. (1) that near T_c the peak amplitude during rotation can be written as $I_\Omega \propto (\Gamma_H + \Gamma_\Omega)^{-1}$ where $\Gamma_\Omega \propto \Omega(1-T/T_c)$.

The very regular behavior of $\Delta I/I$ as a function of Ω strongly suggests that we are dealing with vortices; their density, n, should increase as Ω increases. We can think of several possible explanations for the additional broadening due to rotation but all of them require the existence of vortices. In fact, NMR line broadening has also been seen in experiments[7,8] of superflow at supercritical velocities: A large number of vortices should have been present during these measurements. We can, however, study this effect systematically by varying n.

According to a recent theory by Fomin and Kamensky,[9] vortices can cause broadening of the NMR line for two reasons: They scatter spin waves and the textural nonuniformity caused by vortices results in an increased attenuation of spin waves through spin diffusion.

Both effects depend on the density of vortices, but their temperature dependence is rather complex because of the competition of these two mechanisms and their complicated dependence on the spin-diffusion coefficient, which is not very well known. The calculated broadening is of the right order of magnitude although it cannot be quantitatively compared with our experimental results because the scattering amplitude of spin waves on vortex lines is not known well enough. The actual dependence of the broadening on Ω might, moreover, be different when there is a random or regular array of vortices.

Another possibility is a satellite peak caused by a localized spin-wave mode in the vortex core, resembling solitons.[10] One may argue that at least part of the additional broadening of the NMR line due to rotation results from a splitting, $\Delta\omega$, of the peak within our finite linewidth. The intensity of the satellite peak, which cannot be resolved, is expected to be proportional to n which, in turn, is proportional to Ω. Dimensional analysis gives $\Delta I/I \propto n\xi_D{}^2 F(\Delta\omega/\Gamma_H)$ for the relative decrease of the main ^{3}He-A resonance peak height, where ξ_D is the dipolar coherence length and F is some function.

Equation (1) shows that $F(\Delta\omega/\Gamma_H) \cong \Delta\omega/\Gamma_H$ when $\Delta\omega/\Gamma_H$ is small. $\Delta\omega$, in turn should be proportional to the square of the longitudinal resonance frequency, $\Omega_L{}^2$, i.e., proportional to $1-T/T_c$ as in Eq. (1). If we write, like in the case of solitons, the frequency of the satellite as $\omega^2 = (\gamma H)^2 + R^2\Omega_L{}^2$, one finds that R^2 must be of the order 0.98 to explain at least part of the line broadening. Theoretically we expect the intensity of the satellite to be of the order of S_{core}/S_Ω, where $S_{\text{core}} \cong \pi\xi_D{}^2$ and $S_\Omega = h/4m_3\Omega$ is the area per unit vortex. At our rotation speeds the theoretical intensity of the satellite is rather small, of the order of one percent or less of the main peak.

It seems that the possible existence of this satellite cannot alone explain the large changes in our NMR spectra. We believe that the broadening mechanisms suggested by Fomin and Kamensky[9] are mainly responsible for the reduction in the peak height. Solitons are not a likely explanation, because these structures should be created irregularly, for example, during a sharp acceleration; they cannot easily be responsible for the regular behavior shown in Fig. 3. We did not observe any irregularities in the ^{3}He-A NMR signal due to rapid cool downs or sharp accelerations. However, at low rotation speeds, $\Omega \lesssim 0.2$ rad/s, we found irregularities in $\Delta I/I$. These can be a manifestation of a critical velocity for vortex formation at this speed of rotation, corresponding to a maximum linear velocity of roughly 0.5 mm/s.

Metastability effects were observed when the sample was cooled from the normal Fermi-liquid region to the *A* phase under rotation. The decrease in the peak amplitude was then considerably larger than when rotation was started in the *A* phase during the warmup period. This might be explained by the different vortex species that exist in ^{3}He-*A* in a strong magnetic field. Singular vortices should be created when the transition from the normal to the superfluid phase takes place during rotation. These energetically most favorable vortices have a sharp singular core, the radius of which is of the order of the coherence length ξ, inside a smooth core of radius ξ_D. On the other hand, if rotation is started when the sample is in the superfluid phase, nonsingular vortices with a smooth core of radius ξ_D will be more easily created and hence they are favored.

Preliminary measurements indicate that in rotating ^{3}He-*B* the amplitude of the NMR peak also decreases. The relaxation time for the change is, however, rather long in comparison with ^{3}He-*A*. This could be due to the fact that in ^{3}He-*B* only singular vortices are present.[11] Furthermore, during rotation we observe satellites on the high-frequency side of the peak.[12]

Rotation experiments on the superfluid phases of ^{3}He might be interesting from an astrophysical viewpoint: It is believed that the cores of pulsars contain neutron superfluid.[13] Thus one might simulate pulsars in a laboratory with rotating superfluid ^{3}He which obeys Fermi statistics like neutrons, although the expected superfluidity pairings are not exactly the same.

We acknowledge valuable discussions with A. I. Ahonen, Yu. M. Bunkov, I. A. Fomin, G. A. Kharadze, D. D. Osheroff, and J. C. Wheatley and experimental help by S. T. Kauntola and H. K. Seppälä. This work was supported in part by the Finnish-Soviet Commission for Scientific and Technical Cooperation, by the Academy of Finland, and by the Academy of Sciences of the U.S.S.R. The late V. P. Peshkov was instrumental in getting this joint project started. Two of us (O.T.I. and T.K.M.) are grateful to the Finnish Cultural Foundation for scholarships.

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