NMR in rotating superfluid ^{3}He-B

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The effect of rotation on the shape of the NMR line of ^{3}He-B has been studied. The rotation alters the frequencies of the satellite peaks which are associated with the excitation of standing spin waves. It is suggested that the presence of singular vortices in superfluid ^{3}He-B alters the characteristics of the spin waves.

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A rotating nuclear-demagnetization cryostat has been developed in the Low-Temperature Laboratory of Helsinki Technical University for studying the hydrodynamics of the rotation of superfluid ^{3}He as part of the ROTA Soviet–Finnish project. The properties of superfluid ^{3}He can be studied in this cryostat.[1] When the vessel holding the superfluid helium is rotated, vortices should appear in the helium. One of the methods available for detecting the vortices is to observe changes in the nuclear-magnetic-resonance (NMR) signal in the ^{3}He. A broadening of the NMR line during rotation was observed in the first experiments[2] carried out to monitor NMR in rotating superfluid ^{3}He-*A*. Our purpose in the present experiments was to study the effect of rotation on the NMR in the *B* phase of superfluid ^{3}He.

The experiments were carried out in a cylindrical chamber 5 mm in diameter and 30 mm long. A magnetic field of 284 Oe was applied along the chamber axis. Some auxiliary correction coils improved the uniformity of the magnetic field to 5×10^{-5}, which corresponds to an NMR linewidth of 40-45 Hz for normal ^{3}He. The chamber was installed along the cryostat rotation axis; the rotation axis and the chamber axis were coincident within 1.5 mm. The rotation frequency was varied over the range 0.3-1.4 rad/s. The fluctuations in the rotation frequency were no more than 2.5% over a period.

All the experiments described by us in this letter were carried out in superfluid ^{3}He-*B* at a pressure of 29.3 bar. The temperature was measured with a platinum thermometer[3] calibrated on the basis of the temperature (T_c) at which ^{3}He becomes a superfluid. The ^{3}He sample was cooled to a temperature on the order of 1.3 mK. The cryostat was then alternately rotated and stopped, for time intervals on the order of a few minutes, while the sample warmed up. At the same time, the external magnetic field was scanned at a frequency of one pass per minute, and the transverse NMR absorption signal was measured.

The NMR line usually had an irregular shape immediately after cooling. After rotation at velocities greater than 0.2-0.3 rad/s, however, the line became regular (Fig. 1) and remained regular throughout the rest of the experiment. The shape of the NMR line corresponds in a qualitative way to a conical flare-out of the vector[4] **n**, with the signal reaching a peak at the Larmor frequency and having a high-frequency tail. Clearly visible against the background of this signal are satellite peaks at roughly identical distances, which we will call $\Delta\nu$. Following Osheroff,[5] we attribute these satellite peaks to the excitation of standing spin waves.

We were able to measure the dependence of the separation of these satellite peaks on the peaks on the temperature and on the rotation frequency. Figure 2 shows the temperature dependence $\Delta\nu$ for rotation at various frequencies Ω and in a fixed cryostat. We see that $\Delta\nu$ is extremely sensitive to the rotation frequency and is discontinuous at a temperature of about $0.6T_c$. We also carried out some experiments in which the cryostat was rotated continuously throughout the warming cycle. In these experiments the discontinuity in $\Delta\nu$ was smoothed over.

Figure 3 shows the dependence of the spacing of the satellite peaks on the rotation velocity. According to these results, $\Delta\nu$ is a linear function of Ω at $\Omega > 0.2$-0.3 rad/s. The difference between the values for $T > 0.6T_c$ and $T < 0.6T_c$ results from the sharp change in the slope of the $\Delta\nu(\Omega)$ curves.

In this connection it may be suggested that the rotation velocty ~0.2-0.3 rad/s (which corresponds to a linear velocity of 0.5-0.8 mm/s for the chamber wall) is a critical rotation velocity for the superfluid component of ^{3}He-*B* under these experimental conditions.

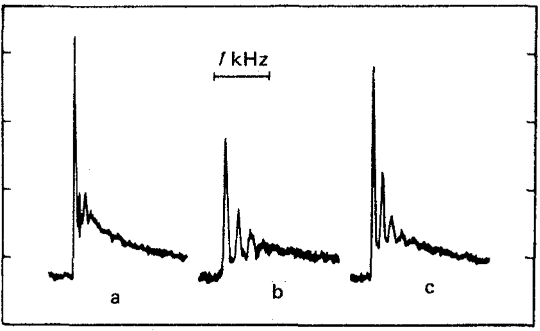

FIG. 1. Shape of the NMR absorption line of ^{3}He as a function of the frequency. In all three cases the temperature corresponds to $T/T_c \approx 0.550$. a–The irregular line shape immediately after cooling to the *B* phase; b–typical line shape corresponding to rotation at the velocity $\Omega = 0.60$ rad/s; c–typical line shape when the fluid is at rest.

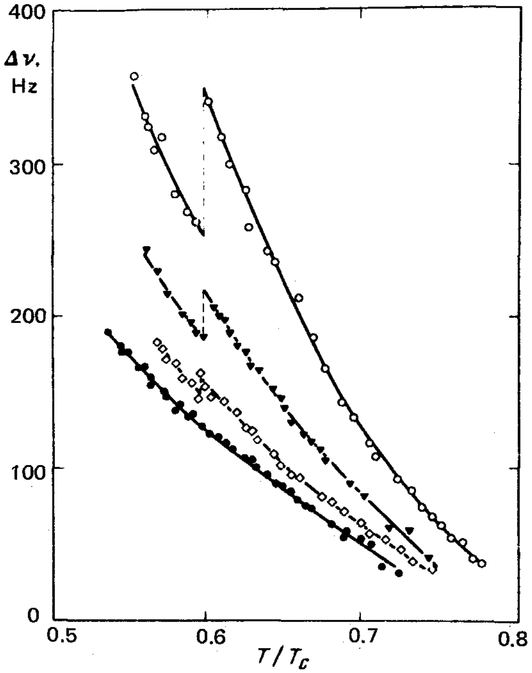

FIG. 2. The splitting $\Delta\nu$ as a function of the temperature. The solid and dashed curves are the envelopes of the experimental points. ○—$\Omega = 1.33$ rad/s; ▼—0.70 rad/s; ◇—0.41 rad/s; ●—at rest.

After the rotation begins, there is a transient stage for 1-2 min, during which the shape of the NMR line changes sharply. This effect occurs at rotation velocities above 0.2-0.3 rad/s. According to our preliminary data, the change in the line shape can be attributed to a deviation of the vector **n** from its equilibrium position **n** ‖ **H** by an angle $\phi \sim 50°$, followed by a return to the equilibrium position.

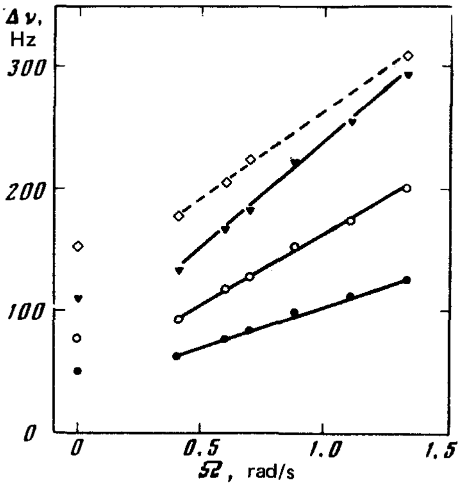

FIG. 3. Dependence of the splitting $\Delta\nu$ on the angular rotation velocity. The measurements are not reproducible at velocities $0 < \Omega \lesssim 0.3$ rad/s. ◇—$T/T_c = 0.57$; ▼—$T/T_c = 0.62$; ○—$T/T_c = 0.66$; ●—$T/T_c = 0.70$.

We believe that immediately after the rotation begins the complete entrainment of the normal component gives rise to a nonequilibrium, vortex-free state for a certain time interval, with a rigid-body distribution of the superfluid velocity $v_s = \Omega r$ with respect to the vessel. It follows from Ref. 6 that a superfluid flow with $v_s > v_c \simeq 1$ mm/s has an orienting effect on the **n** anisotropy axis and is capable of competing with the orienting effect of an external magnetic field. For this reason, we should expect a significant deviation of the distribution of the field **n** from its original configuration, in the vessel at rest, over distances greater than $r_c = v_c/\Omega$ from the rotation axis. (Since the condition $r_c < R$ holds for these experimental conditions, the substantial change in the structure of the NMR spectrum which is observed early in the rotation can be attributed to the occurrence of these nonequilibrium superfluid flows.)

The restoration of the original structure of the NMR spectrum implies the formation of an equilibrium vortex structure. In this state, there is a rigid-body (on the average) rotation of the superfluid component in the laboratory coordinate system, so that in the coordinate system which is rotating along with the vessel there are only relatively slight superfluid flows, which cannot significantly affect the orientation of **n** at these rotation velocities.[7]

The regular changes, dependent on the rotation velocity, of the resonant frequencies of the standing spin waves are a consequence not of these flows but of the strong effect on the distribution of the field **n** in the vessel exerted by the rigid cores of the vortices, with a radius on the order of the coherence length ξ. Evidence for this conclusion comes from the transition, which occurs only during rotation and always at the same temperature. These events would be possible if the transition were due not to a structural change in the system of vortices (the temperature of such a transition would depend on the density of the vortices) but to the individual properties of a vortex, i.e., a structural change within a vortex core.

The experimental data are evidence of a complex structure of the core in the B phase and of a long-range effect of this core on the distribution of the field **n** in the vessel. These two circumstances are closely related. The complex core structure means that the change in the order parameter A_{ik} in the core is not of the simple form $A_{ik} = C_{(r)} R_{ik} \exp(i\Phi)$, where $C(r)$ vanishes at the vortex axis ($r \rightarrow 0$). In general, a situation in which A_{ik} does not vanish at all is apparently preferred. Within the core, the spin structure of the order parameter is also subject to changes; as a result, the core is a source of deformation for the matrix R_{ik}, including the vector **n**. These deformations of the field **n** may distort the texture at distances out to the magnetic length R_H. The effective distortions of the texture are proportional to the density of eddies, so that the spacing of the satellite peaks in the NMR signal of ^{3}He-B depends on the rotation velocity.

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