because of the uncertainties in Z_{eff}.

Analysis of the waveguide coupler shows that the lower-hybrid waves should interact primarily with electrons with energies greater than 30 keV. This prediction is consistent with the x-ray and microwave radiation spectra. How the electrons from the 1-keV background plasma are raised to this energy has yet to be explained in this experiment and indeed is one of the principal unresolved problems in rf current drive.

This work represents a very significant step in the development of a steady-state current drive for tokamak plasmas. Discharges have been produced in which essentially all of the power to maintain a high current is derived from the rf fields for periods up to 3 sec. There is strong evidence that the current is carried by high-energy (~100-keV) electrons, which are concentrated in the inner core of the discharge.

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Experiments on Vortices in Rotating Superfluid ^{3}He-A

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A satellite peak has been observed in the NMR spectrum of rotating ^{3}He-A; the peak intensity depends linearly on Ω at the high angular velocities, $\Omega = 0.6$–1.5 rad/s, needed to resolve it. The frequency shift of the satellite is independent of Ω. These results strongly suggest the existence of vortices in rotating ^{3}He-A with the vortex density proportional to Ω. Another satellite peak also has been observed which probably is due to solitons.

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Singularities in superfluid ^{3}He, as well as in other ordered media, have interested experimentalists and theorists during recent years.[1-7] However, because of the experimental difficulties, rotating superfluid ^{3}He has not been explored until very recently. Rotation is a well-defined way to produce singularities in superfluids and, in addition, creation of singularities

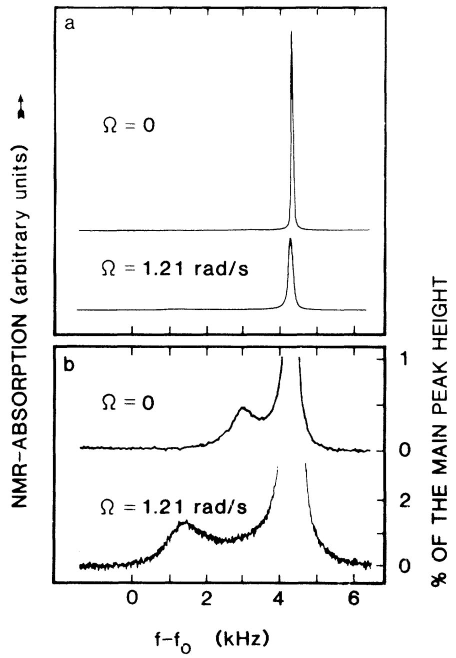

FIG. 1. Transverse NMR absorption line shapes at $1-T/T_c = 0.267$ as a function of frequency showing the satellite peaks as well as the Ω-dependent broadening of the main A-phase peak. Part (b) is a closeup of part (a), showing the soliton peak at Ω = 0 and the vortex peak at Ω = 1.21 rad/s. In the latter case the soliton peak has already decayed.

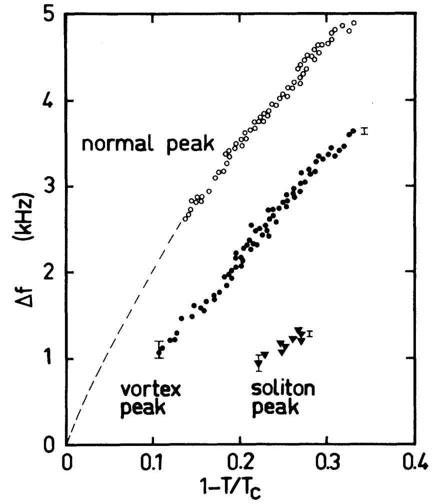

FIG. 2. Frequency shift of the satellites as a function of T measured with Ω = 0.6–1.43 rad/s after cooldown to the A phase either at rest or under rotation. For experimental reasons the figure shows the frequency shifts of the satellites and the position of the normal liquid peak relative to the bulk A-phase peak. The dashed line is interpolated from the result by Ahonen, Krusius, and Paalanen (Ref. 10).

is intimately connected with rotation of the superfluid component. Theory predicts that in rotating ^{3}He-A either singular or nonsingular vortices are formed, depending on external conditions.[3]

We expected that these structures could be detected by nuclear-magnetic-resonance techniques.[4] Our optimism was motivated by experiments in which characteristic NMR satellite peaks, due to textural singularities, have been observed.[5-7]

In this Letter we report the discovery of a satellite NMR peak in rotating ^{3}He-A. The satellite is observed in addition to the Ω-dependent broadening of the main peak described earlier.[8] This satellite remained unobserved in our previous experiments because its amplitude is very small.

The measurements were performed in a rotating nuclear demagnetization cryostat.[9] The experimental space was cylindrical, 5 mm in diameter and 30 mm in length. We performed transverse cw NMR measurements by modulating the axial magnetic field around $H_0 = 284$ Oe. The pressure was 29.3 bars. The A phase was entered from the Fermi-liquid region with the cryostat either at rest or under rotation at a fixed Ω. A high velocity, between 0.6 and 1.5 rad/s, was needed to resolve the satellite.

Actually, we observed two different satellite peaks between the Larmor frequency f_0 and the bulk A-phase frequency $f_A = (f_0^2 + f_L^2)^{1/2}$, where f_L is the longitudinal resonance frequency (see Fig. 1).

One satellite was observed only during rotation; its frequency shift and intensity behaved reproducibly. Because this satellite is broad, it can be seen as a separate peak only sufficiently far from T_c, mainly in supercooled ^{3}He-A, where the bulk A-phase frequency shift is large. We call this satellite the vortex peak for reasons which will become clear later.

The other satellite also has a well-defined frequency shift but its intensity drastically changes from one experiment to another. This satellite appears most clearly after a quick cooldown at rest to the A phase. The peak intensity decreases with time, most of it disappearing in about half an hour during rotation. We call this satellite the soliton peak for reasons to be explained later.

The frequency shifts of the satellites were studied as functions of T and Ω; experimentally it was easiest to measure $\Delta f = f_A - f_{\rm stl}$. Figure 2 shows Δf for the vortex peak and for the soliton peak. Within our accuracy Δf for the vortex peak depends neither on Ω nor on whether the sample was cooled to the A phase at rest or while rotating.

We have also investigated the intensity of the vortex peak as a function of Ω. The vortex peak and the main peak partially overlap. Since the main peak is also affected by rotation[8] and it is nonsymmetric, we estimated the satellite intensity I_{stl} by the method illustrated in the inset of Fig. 3. It seems to us that this method of analysis provides a consistent way to compare intensities at different Ω's and it should, moreover, give a reasonable estimate of the satellite intensity because at low temperatures, where the peaks are well separted, the satellite appears roughly symmetric. The measured intensities are scattered by $\pm 10\%$ at $\Omega = 1.4$ rad/s and by $\pm 30\%$ at $\Omega = 0.6$ rad/s. These error limits include a slight increase in I_{stl} with temperature which might be due to the increasing overlap with the main peak. Therefore, the intensity analysis was restricted to low enough T, mainly $1 - T/T_c > 0.2$.

Figure 3 shows averaged values of vortex peak intensities normalized to the total NMR absorption, as functions of Ω. The closed and open symbols represent experiments during which the A phase was entered from the Fermi liquid either at rest or while rotating at a fixed Ω, respectively. In the first case a linear dependence on Ω is observed, with $I_{\text{stl}}/I_{\text{tot}} = 0.058\Omega/(\text{rad/s})$. In the second case the points seem to fall systematically above this line. The half width at half maximum of the vortex peak (see the inset of Fig. 3) is about 1 kHz, independent of Ω.

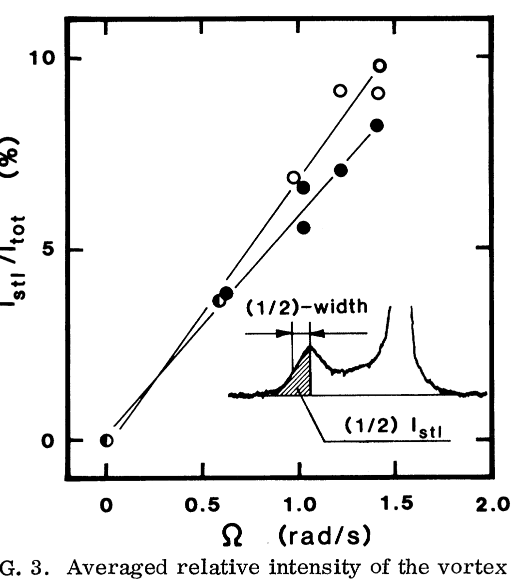

FIG. 3. Averaged relative intensity of the vortex peak as a function of Ω. The closed symbols correspond to the case when the rotation was started in the A phase, while the open symbols are data from experiments where the sample was cooled to the A phase while rotating at a fixed Ω. Error bars are roughly of the size of the symbols and refer to the relative intensities at different Ω calculated by the method shown in the inset.

The time scale for changes in the NMR signal is quite rapid; with our acceleration and deceleration, 0.03 rad/s^2, the vortex peak height followed roughly the instantaneous speed of the cryostat, with a few seconds time lag at most.

In stationary ^{3}He-A Gould and Lee[7] have reported a transverse NMR satellite in an open cylinder, with the magnetic field perpendicular to its axis. The frequency shift could be described by the parameter $R_t = (f_{\text{stl}} - f_0^2)^{1/2}/f_L$, having a temperature-independent value of $R_t = 0.835$. Maki and Kumar[1] explained this by composite solitons which are textural domain walls. Such a dipole-unlocked[11] region forms a potential well which can trap localized spin waves, thus producing a well-defined NMR satellite frequency. The value of R_t is characteristic of different solitons and of dipole-unlocked textures; it can be used to classify them.[1]

We find for our soliton peak $R_t = 0.846 \pm 9.015$ which is close to the value of Gould and Lee. This suggests that the satellite is caused by solitons which might be created by our quick cooldown to the A phase; it has been observed that rapid temperature changes increase the intensity of the soliton satellite.[7] However, large textural changes brought about by flow during rotation appear to destabilize the solitons.

For vortex peaks the R_t value is substantially smaller. R_t changes from 0.53 at $1 - T/T_c \cong 0.30$ to 0.70 at $1 - T/T_c \cong 0.15$, the error estimates being ± 0.01 and $+0.03$, -0.05, respectively. It is not likely that these satellites are due to solitons, because the types of solitons expected in an open cylindrical vessel should produce larger values of R_t.[1] Solitons might be formed irregularly during a sharp acceleration but they would in that case not be manifested in the regular fashion shown in Fig. 3.

Bruinsma and Maki[12] showed that dipole-locked linear textures are not capable of causing large negative frequency shifts from f_A. Pointlike singularities probably cannot produce a satellite peak as large as we observe. Consequently, we think that there must be dipole-unlocked linear textures in our rotating sample, their number and thus also their combined volume increasing linearly with Ω; this, in turn, would cause the satellite intensity to be proportional to Ω. It seems to us that the dependence shown in Fig. 3, combined with the result that the satellite frequency does not depend on Ω, is strong evidence for vortices in rotating ^{3}He-A, the number of vortices being proportional to Ω. We believe that the satellite is produced by localized spin-wave modes trapped on each vortex core.

There are, to our knowledge, no detailed predictions of the effect that singular or nonsingular vortices would have on the ^{3}He-A NMR spectrum in a high magnetic field. Therefore, we crudely estimate the relative satellite intensity due to either singular or nonsingular vortices, I_{stl}/I_{tot}, by the ratio S_v/S_0, where S_v is the effective cross-sectional area of the vortex core and S_0 is the primitive cell area of the vortex lattice.[13] We write $S_v = \pi(\lambda\xi_D)^2$, where $\xi_D \cong 6\ \mu$m is the dipolar coherence length and λ is of the order of unity, with its actual value depending on the core structure. Therefore, we obtain the experimentally verified linear Ω dependence $I_{stl}/I_{tot} = \pi(\lambda\xi_D)^2 \times 4m_3\Omega/Nh$, where N is the circulation quantum per vortex. Comparing with our experimental date we find $\lambda \cong 4$ for singular vortices with $N=1$ and $\lambda \cong 6$ for nonsingular vortices with $N=2$. These values of λ are quite large but, taking into account our crude model and the exponential healing of the core texture, they are still plausible.

Calculations with some model textures of rotating ^{3}He-A in an axial H suggest[14,15] dipole-unlocking near each vortex. On the other hand, stationary ^{3}He-A confined to long and narrow ($r < \xi_D$) cylindrical pores must have singular or nonsingular dipole-unlocked linear structures but, in this case, caused by boundary conditions. In such experiments[5,6] two satellite peaks were observed between f_0 and f_A, corresponding to two different linear textures. One of these satellites has the R_t value of the same order as our vortex peak, also supporting linear singularities in our case.

The fact that cooldown to the A phase under rotation produces a systematically larger satellite than cooldown at rest can be evidence of different kinds of vortices in these two cases, or evidence of nonequilibrium effects for singular vortices.[16] The latter structures should be energetically favored in a high axial field,[4] although their formation might be inhibited by a topological energy barrier. However, recent calculations by Seppälä and Volovik[17] suggest the identification with nonsingular vortices, because the investigated singular vortices were not able to produce such large NMR frequency shifts as were observed.

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$$2\Omega S = \int_S d\vec{s}\cdot(\nabla\times\langle\vec{v}_s\rangle) = \sum_{i=1}^{n}\oint d\vec{c}_i\cdot\vec{v}_s = nNh/2m_3,$$

yielding S_0. Stokes's law and quantization of circulation have been employed.

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