Texture of superfluid ^{3}He-B rotating in an inclined magnetic field

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(Submitted 17, March 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 8, 395–399 (20 April 1983)

A study is made of the NMR spectrum of superfluid ^{3}He-B rotating in a magnetic field inclined at an angle of 25° to the axis of rotation. The NMR frequency is observed to shift by an amount which depends on the speed of rotation and represents the effect of singular vortices on the texture of ^{3}He-B.

PACS numbers: 67.50.Fi

The first experiments[1] on NMR in rotating superfluid ^{3}He-B revealed that rotation strongly affects the shape of the NMR signal and, hence, the texture of the order-parameter vector **n**. The NMR signal consists of equidistant peaks whose separation increases when the sample is rotated. It was subsequently shown[2,3] that a potential well, in which standing spin-wave modes are excited, is formed in the central region of the "conically expanding" texture, which occurs in an axial field.[4] Upon rotation, singular vortex lines, which alter the parameters of the potential well and thus the spectrum of the standing spin waves, appear in ^{3}He-B. Unfortunately, one cannot obtain directly from this experiment the value of the energy associated with the orienting effect on the order parameter. An experiment, in which the shift of the fundamental NMR line upon rotation of ^{3}He-B can be observed in an inclined field was proposed[5] for quantitative study of this effect. The implementation of this experiment is the subject of this paper.

If one considers only the volume terms in the free energy which orient the vector **n**, the magnetic energy $F_{\mathbf{H}} = -a(\mathbf{n}\cdot\mathbf{H})^2$ and the energy of interaction with the vortices, taken in the form $F_v = \frac{2}{5}a\lambda\,(\Omega_i R_{ik}\mathbf{H}_k)^2$, proposed by Gongadze *et al.*,[6] the minimization of $F_{\mathbf{H}} + F_v$ gives a solution in which **n** is inclined to **H** at an angle β such that

$$1/\lambda = u\cos 2\mu + (u^2 - {}^1/_2)\,(1 - u^2)^{-1/2}\sin 2\mu\,;\; u = 1 - ({}^5/_4)\sin^2\beta\,, \qquad (1)$$

where μ is the angle between the axis of rotation Ω and **H**. The frequency of the NMR signal should thus be shifted on account of the rotation by an amount

$$\Delta\nu \cong \frac{(\nu_L^B)^2\sin^2\beta}{2\nu_0}\,,$$

where ν_L^B is the Legett frequency of the longitudinal NMR in ^{3}He-B. There remains the question of the effect on the texture due to the interaction energy between **n** and the walls of the chamber, which we shall now consider on the basis of the experimental data.

Experimental results

The experimental chamber (see Refs. 1 and 4) was 5 mm in diameter and 30 mm in length. It was held at a pressure of 29.3 bar and placed in a magnetic field of 28.4 mT which was inclined at an angle of 25.0°, corresponding to the maximum shift of the NMR frequency for the anticipated value of λ. The shift of the NMR frequency ν_t of the ^{3}He-B in the experimental chamber with respect to the Larmor frequency ν_0 was measured to an accuracy of $\pm$ 25 Hz. Figure 1 shows, for various speeds of rotation, the frequency shift $\nu_t - \nu_0$ of the NMR absorption peak divided by the frequency of the longitudinal resonance in ^{3}He-B, so that what is plotted is the quantity

$$\sin^2\beta \cong \frac{\nu_t^2 - \nu_0^2}{(\nu_L^B)^2} \cong 2\nu_0\frac{\nu_t - \nu_0}{(\nu_L^B)^2}\,. \qquad (2)$$

Each of the curves in Fig. 1 was measured over a single heating cycle, with the temperature increasing at a rate of 50 nK/sec. In order to achieve equilibrium conditions and avoid thermal hysteresis, every 10–20 min the cryostat was stopped and then spun up again at an acceleration of $\sim$0.03–0.04 rad/sec^2.

Figure 2 shows the dependence of the NMR frequency shift on the rotational speed at constant temperatures. In this case each isotherm was taken over a single cooling and heating cycle. The cryostat in this case was spun up and stopped from one speed to the next at the same rate of acceleration as before. The shift of the NMR

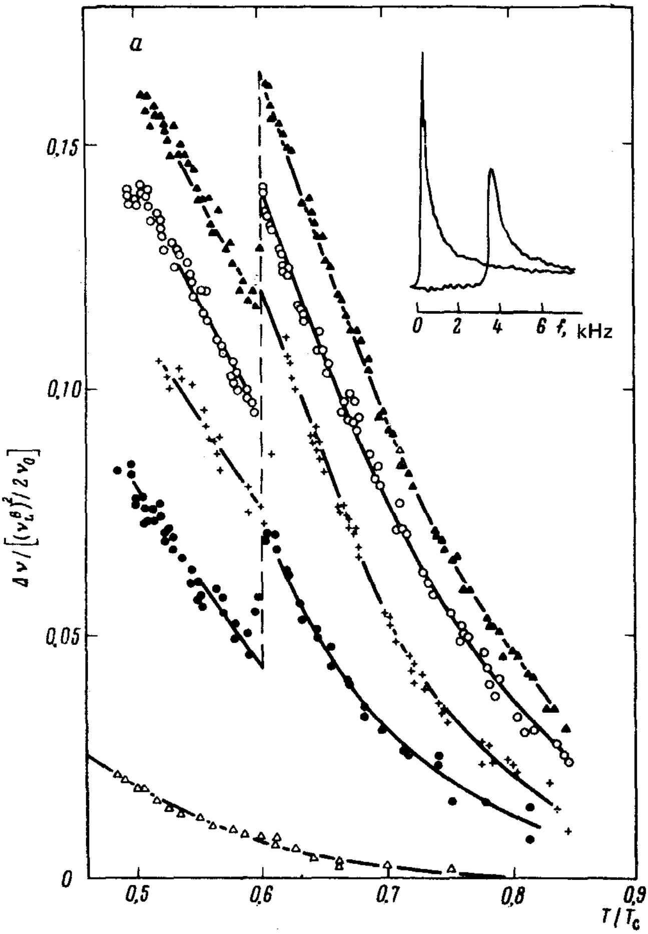

FIG. 1. Shift of the NMR frequency divided by the longitudinal-resonance frequency, plotted as a function of the temperature for various rotational velocities. Δ) $\Omega = 0$; ⊙) $\Omega = 0.85$ rad/sec; +) $\Omega = 1.15$ rad/sec; O) $\Omega = 1.4$ rad/sec; ▲) $\Omega = 1.70$ rad/sec. The lines show the basic trend of the behavior. The inset shows the shape of the NMR absorption signal as a function of the shift of the frequency from the Larmor frequency. These signals were obtained at $\Omega = 0$ (the larger amplitude) and at $\Omega = 1.4$ rad/sec (the larger frequency shift) at $T/T_c = 0.63$.

frequency did not depend perceptibly on whether the cryostat had previously been spinning faster or slower. Thus the data shown in Figs. 1 and 2 were obtained in different cooling cycles of the helium-3.

It is seen in Fig. 1 that under the conditions of the experiment a shift of the NMR frequency was observed even when the cryostat was at rest. The size of the shift varied slightly in different cooling cycles, evidently as a result of changes in the boundary conditions for the vector **n** at the surface of the chamber. This in turn led to scatter in the values of the NMR frequency shift upon rotation as obtained in different cooling cycles.

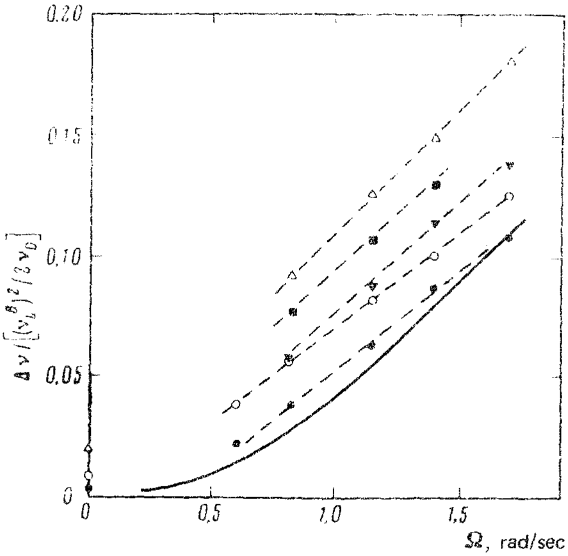

FIG. 2. Shift of the NMR frequency divided by the longitudinal-resonance frequency as a function of the rotational velocity for various temperatures. Δ) $T = 0.5T_c$; ○) $T = 0.58T_c$; ■) $T = 0.62T_c$; ▼) $T = 0.66T_c$; ●) $T = 0.70T_c$. The solid line is the theoretical curve for $T = 0.7T_c$.

Effect of the boundary conditions

Two different textures of ^{3}He-B in an inclined field were clearly recorded in the experiments. When the transition to the B phase occurred in an axial field and the field was then inclined to an angle of 25°, a standing-spin-wave signal of the typical form for a conically expanding texture was observed both during rotation and in the stationary state. No shift of the fundamental NMR absorption line was observed even at angular velocities of 1.7 rad/sec. In an inclined field this texture had a metastable behavior. To destroy the texture, the cryostat had to be spun up at an acceleration of 0.1 rad/sec^2.

When the helium-3 was cooled down to the B phase in a magnetic field inclined at 25° to the axis of the chamber, the NMR signal under rotation was substantially altered. A shift of the NMR frequency from the Larmor frequency was observed, and the standing-spin-wave signal disappeared. Moreover, when the magnetic field was returned to the axial direction, the shift of the NMR signal under rotation persisted.

All of the experimental results presented here refer to the texture in which a shift of the NMR frequency is observed upon rotation. In order to obtain this texture in a stable way, we used the following procedure. During cooling, in the temperature region $\sim 0.65T_c$, the cryostat was spun up to a speed of 1.4 rad/sec at a rate of 0.1 rad/sec^2, and then brought to rest at the same rate of acceleration. The texture obtained in this way was characterized by an NMR signal with the following properties: a relatively sharp peak of the absorption signal during rotation; the absence of a standing-spin-wave signal at frequencies close to the Larmor frequency; the presence of a standing-spin-wave spectrum under stationary conditions at $T \sim 0.65T_c$, with a fundamental level that was shifted from the Larmor frequency by the amount shown in Fig. 1.

We attribute the observed behavior of the texture of the superfluid ^{3}He-B in an inclined field to the localization of the linear singularities predicted in Ref. 5 at the surface of the chamber; in that paper it was shown that at the chamber surface

$$\sin\beta = -(2/\sqrt{5})\sqrt{1 \pm \sin\mu\cos\Phi}, \tag{3}$$

where Φ is the azimuthal angle. For $\mu > 14.5°$, both branches of this solution become discontinuous, and this should lead to singularities at the surface of the chamber.

It follows from Refs. 2–4 that in an axial magnetic field, boundary condition (3) without discontinuities leads to the conically expanding texture. When the magnetic field is then inclined, this texture remains metastable.

On the other hand, if singular lines have formed on the surface and the solution of type (3) has become discontinuous, the vector **n** evidently undergoes an azimuthal inclination in opposite directions at opposite walls of the chamber. As a result, the texture of the vector **n** at the center of the chamber no longer corresponds to the

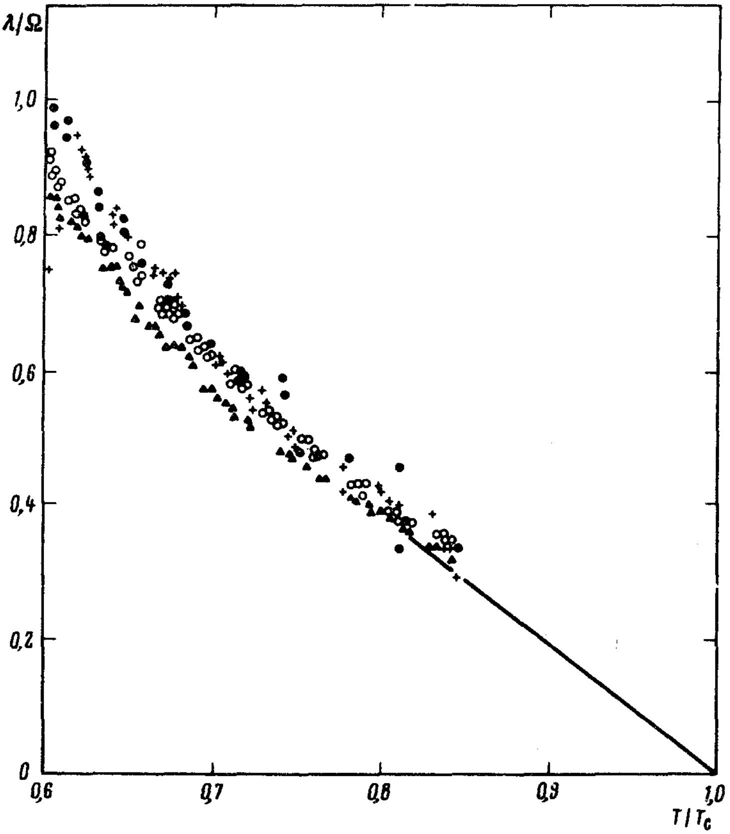

FIG. 3. Temperature dependence of the parameter λ/Ω, obtained by a recasting of the data with the aid of Eq. (1). The straight line corresponds to the function $\lambda/\Omega = 2.0(1 - T/T_c)$. ▲) $\Omega = 1.7$ rad/sec; O) $\Omega = 1.4$ rad/sec; +) $\Omega = 1.15$ rad/sec; ●) $\Omega = 0.85$ rad/sec.

conditions of free ^{3}He. Therefore, upon rotation in this case a shift of the NMR frequencies can be seen.

The orienting effect of the surface decays exponentially in the volume of ^{3}He. At a temperature $T = 0.5T_c$ the penetration depth ξ_H reaches 1/4 of the radius of our chamber. For this reason, the contribution of the surface energy to the NMR frequency shift is important at low temperatures, as can readily be seen from the temperature dependence of the NMR frequency in the stationary cryostat. However, at higher temperature the contribution of the surface energy falls off rapidly, and at $T \gtrsim 0.7T_c$ the conditions at the center of the chamber for the given texture essentially correspond to free ^{3}He.

Using Eq. (1), we converted the data on the shift of the NMR frequency shift under rotation (Fig. 1) to the quantity λ/Ω (Fig. 3). In the high-temperature region the points are well described by the dependence $\lambda/\Omega = 2.0(1 - T/T_c)$. Using this value for the parameter λ, the theoretical dependence of the frequency shift on the rotational velocity was constructed for a temperature of $0.7T_c$ (the solid curve in Fig. 2). In the low-temperature region there is a systematic deviation of the experimental points for λ/Ω to higher values; this is evidently due to the growing influence of surface effects that were not included in Eq. (1). The influence of these effects is more noticeable at small rotational speeds because of the correspondingly smaller vortex density.

At temperatures $T > 0.6T_c$ the size of the NMR frequency shift does not depend (within the experimental accuracy) on the direction of rotation of the cryostat. However, for $T < 0.6T_c$ this quantity was observed to depend strongly on the direction of rotation, indicating the presence of orbital effects in ^{3}He-*B*. These effects are not considered in this article, as they require further study.

In summary, the information obtained in the experiments on the rotation of ^{3}He-*B* in axial and inclined magnetic fields indicates that the free energy contains a term of the form $(\hat{\Omega}_i R_{ik} H_k)^2$, which is due to singular vortex lines. Under the experimental conditions described in this article, the superfluid ^{3}He-*B*, at least in the high-temperature region, can be considered free, i.e., the energy of interaction between the vortex lines and the order parameter can be described in terms of the energy of free He^3. The interpretation of the results at lower temperatures in complicated by the phase transition at $T = 0.6T_c$. We hope that further studies will elucidate the cause of this effect.

We are grateful to A. D. Gongadze, M. Salomaa, and G. E. Volovik for the discussions which stimulated these studies and to H. Senpala for assistance in the experiments.

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Translated by Steve Torstveit
Edited by S. J. Amoretty