Long-lived induction signal in superfluid ^{3}He-B

A. S. Borovik-Romanov, Yu. M. Bun'kov, V. V. Dmitriev,
and Yu. M. Mukharskiĭ
Institute of Physical Problems, Academy of Sciences of the USSR

(Submitted 16 August 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 6, 256–259 (25 September 1984)

The frequency of the "long-lived" induction signal in ^{3}He-B depends on the time, and the rate of change of this frequency increases with increasing field gradient. Experiments confirm Fomin's theoretical explanation of this phenomenon, according to which a ^{3}He-B sample in which a uniform magnetization precession is excited breaks up into two phases. In one, the magnetization is parallel to the field and does not precess; in the other, the magnetization processes with a deflection angle of approximately 104°.

In normal ^{3}He the nuclear induction signal which appears after a deflection of the spin system by an rf pulse decays over a time determined by the nonuniformity of the static external magnetic field **H**. In superfluid ^{3}He-B, in contrast, the induction signal is observed to decay much more slowly. The duration of this unusual induction signal, which was detected in Refs. 1 and 2, can be as long as a second. The long-lived part of the signal has an intensity $\sim 10\%$ of the initial intensity. Corruccini and Osheroff[1] have attributed this signal to textural effects. In the experiments reported by us here the intensity of the long-lived part of the induction signal reached 90–95% of the initial intensity of the induction signal, and an explanation in terms of textural features no longer suffices.

The present experiments were carried out in magnetic fields of 77, 154, and 276 Oe (corresponding to NMR frequencies of 250, 500, and 850 kHz) at pressures of 20 and 29.3 bar in the cell holding the ^{3}He.

The necessary temperature (0.5–2 mK) was reached with the help of a nuclear demagnetization cryostat and was measured with a PLM-3 NMR thermometer. The experiments were carried out in various experimental cells. Cell 1 (Fig. 1a) is a cylinder with an inside diameter of 5 mm and a length of 13 mm. It is connected to the rest of the experimental chamber by a channel 2 mm in diameter. The transmitting and receiving rf coil of the pulsed NMR spectrometer is wound around the generatrix of the cylinder. The rf field is uniform within 1% over the greater part of the cell. The static external magnetic field is directed perpendicular to the axis of the cylinder. The free induction signal is detected by a Datalab 905 storage oscilloscope and fed to a computer.

Over several milliseconds (after the deflection of the spin system of the ^{3}He nuclei by the rf pulse) the induction signal falls off roughly in accordance with the nonuniformity of H. At this point, however, the rate of decay of the induction signal decreases sharply (in some cases the signal in fact increases): A long-lived induction signal is formed. The length of this long-lived signal reaches 0.5 s in the most uniform field

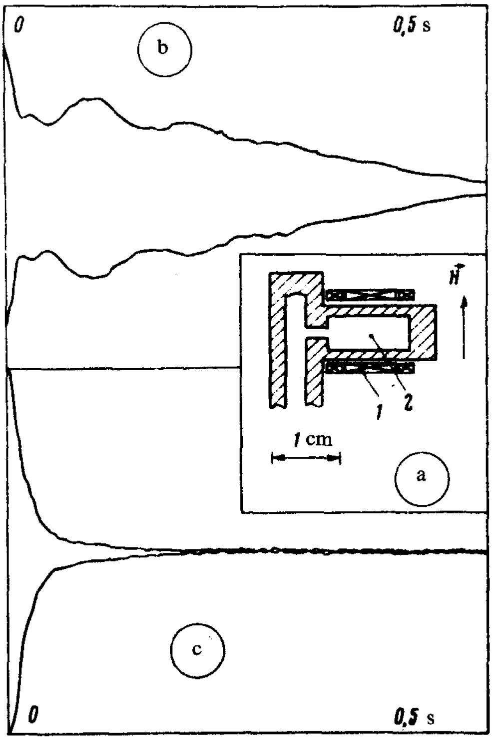

FIG. 1. a: Cell 1. 1—The rf coil; 2—the volume with the ^{3}He. b: Envelope of the long-lived induction signal in ^{3}He-B at $T = 1.8$ mK ($0.7T_c$). $P = 29.3$ bar. The initial magnetization deflection angle is $\beta_0 = 90°$. c: Envelope of the nuclear induction signal under the same conditions in normal ^{3}He ($T = 3$ mK).

under our conditions (Figs. 1b and 1c) and decreases when a field gradient is introduced. The intensity of this long-lived signal increases rapidly with increasing initial deflection angle β_0 up to $\beta_0 \sim 104°$, where the long-lived signal has an intensity 90–95% of the initial intensity. At $\beta_0 \lesssim 30°$ we do not observe the long-lived signal. A result of importance for reaching an understanding of the long-lived signal is that the frequency of the long-lived signal decreases over time approximately linearly if there is a linear gradient in H. The rate of change of the frequency increases with increasing value of $\nabla|H|$. All these properties of the long-lived signal can be explained well by the theory proposed by Fomin.[3] According to this theory, when there is a linear gradient in H a loss of phase coherence in the spin system is unfavorable from the energy standpoint. When phase coherence is lost, superfluid spin currents are excited and flow along the direction of the field gradient, carrying magnetization from one part of the sample into another. The result is the partitioning (with the total Zeeman energy conserved) of the ^{3}He sample into two uniform parts which differ in the magnitude of the longitudinal magnetization (for brevity, we will call these parts phases 1 and 2). In phase 1 we have $\beta = 0$, and in phase 2 we have $\beta \geqslant 104°$. The transverse magnetization of phase 2, whose spins precess in phase, induces the long-lived induction signal in the rf coil. The positions of the phases are determined unambiguously by the direction of the field gradient: Phase 1 arises in the part of the sample in which the

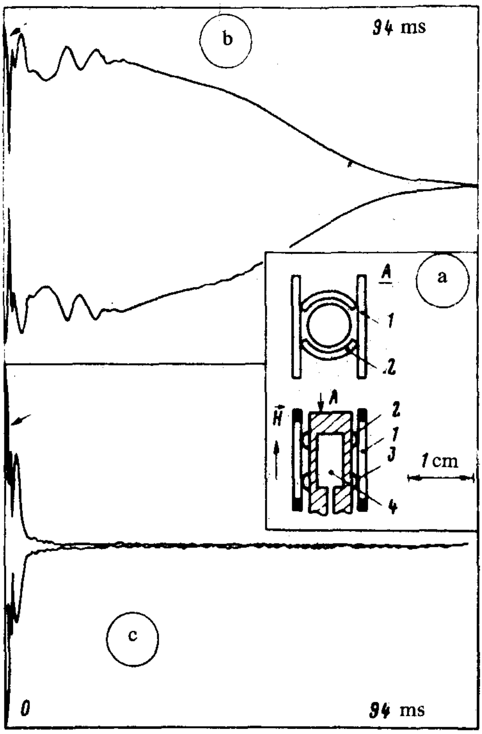

FIG. 2. a: Cell 2. 1—The exciting rf coil; 2, 3—saddle-shaped receiving rf coils; 4—volume with ^{3}He. b, c: Induction signals from coils 2 and 3, respectively, measured after the application of the deflecting rf pulse ($\beta_0 = 100°$) to coil 1. $T = 0.74T_c$, $H = 154$ Oe, $P = 20$ bar, $\nabla H = 0.9$ Oe/cm.

average field is higher. The magnetization precession frequency of phase 2 is γH_0, where H_0 is the field at the boundary between the phases. Relaxation accounts for the motion of the boundary and thus a decrease in the intensity of the long-lived signal and a change in the frequency of the signal because of the field gradient.[3]

In order to obtain direct confirmation of Fomin's theory, we carried out some further experiments with a new ^{3}He test cell (Fig. 2a). This cell, a cylinder 4 mm in diameter and 8 mm long, was connected to the rest of the test chamber by a long (~5-mm), narrow (1-mm-diameter) channel. We used three rf coils in these experiments. Coil 1 (Fig. 2) produces an rf field which is uniform within 1% over the entire volume of the cell. This coil is used primarily as the exciting coil. Saddle-shaped coils 2 and 3, with identical characteristics, are used primarily as the receiving coils; their regions of sensitivity do not overlap. All these coils thus receive an induction signal from the two parts of the ^{3}He sample in the cell. The external magnetic field is oriented along the axis of the cylinder. Figure 2b shows the envelopes of the induction signals taken from coils 2 and 3 after the application of a deflecting rf pulse to coil 1. The direction of the gradient in H was chosen in such a way that phase 2 would form in the upper part of the cell. It can be seen from this figure that the induction signals received by coils 2 and 3 are of greatly different length. Let us examine the events that occur in the ^{3}He in the cell after the deflecting pulse is applied. Over the first few milliseconds (before the

^{3}He volume is broken up into two phases) both of the coils receive an induction signal which decays rapidly over time because of the spatial loss of phase coherence (the rapid decay of the signal from each coil in the very early stage is marked by the arrows in Figs. 2b and 2c).

The ^{3}He sample then breaks up into two phases. Since the initial deflection angle is $\beta_0 = 100°$, phase 2 fills essentially the entire volume of the cell and the sensitivity region of not only coil 2 but coil 3. The spins in phase 2 rapidly come into phase (there is a rapid increase in the induction signal in each coil). The motion of the boundary between the phases has the consequence that the sensitivity region of coil 3 becomes filled with phase 1, which has no transverse magnetization ($\beta = 0$), and the signal at coil 3 rapidly disappears. The signal at coil 2 begins to fall off only when the boundary between the phases reaches its sensitivity region. When the sign of the gradient in H is reversed, coils 2 and 3 exchange roles: The long-lived induction signal is clearly seen at coil 3 but is absent from coil 2. We have thus been able to experimentally observe the partitioning of a ^{3}He sample into two phases, which account for the formation the long-lived induction signal.

The change in the frequency of the long-lived signal is related to the motion of the boundary between phases, which in turn results from relaxation processes. Fomin has shown that two relaxation mechanisms are important here: the Leggett and diffusion mechanisms. The diffusion mechanism is predominant in the final part of the long-lived signal. If we take only the diffusion relaxation mechanism into account, we find that the frequency of the long-lived signal is a linear function of the time.[3] Figure 3 shows some typical measurements of the frequency of the long-lived signal versus the time for various values of ∇H. We see that the Leggett relaxation mechanism is important, making the $\omega(t)$ dependence nonlinear.

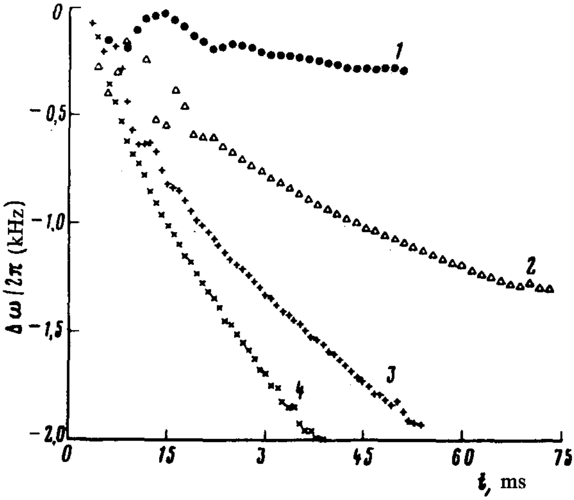

FIG. 3. Time evolution of the frequency of the long-lived induction signal for various values of ∇H. The signal is taken from coil 2. $\beta_0 = 100°$, $T = 0.74T_c$, $H = 154$ Oe, $P = 20$ bar. The field gradient is: 1—0.4 Oe/cm; 2—0.9 Oe/cm; 3—1.65 Oe/cm; 4—2.4 Oe/cm.

In conclusion we wish to call attention to the following circumstance: For an intense long-lived induction signal to form, the test volume holding the ^{3}He on which the rf field acts must be coupled weakly with the rest of the ^{3}He in the chamber, since the superfluid spin currents which arise upon the formation of the long-lived induction signal can carry magnetization directly into the sensitivity region of the rf coils from other parts of the chamber. In our experiments, both of the ^{3}He cells are connected to the rest of the chamber by narrow channels. In the experiments of Refs. 1 and 2 the experimental volumes were open, and this circumstance prevented observation of an intense long-lived signal. It should also be noted that the process by which the ^{3}He sample breaks up into two phases, and a boundary forms between the two phases, is not completely clear. Immediately after the formation of the long-lived signal we often observed oscillations in the amplitude and frequency of the signal. These oscillations may be due to damped oscillations of the boundary between the phases.

We wish to thank I. Fomin for a close and productive collaboration, V. L. Golo and G. A. Kharadze for useful discussions of the results, and S. M. Elagin for assistance in the experiments.

[1] L. R. Corruccini and D. D. Osheroff, Phys. Rev. B **17**, 126 (1978).
[2] R. W. Giannetta, E. N. Smith, and D. M. Lee, J. Low Temp. Phys. **45**, 295 (1981).
[3] I. A. Fomin, Pis'ma Zh. Eksp. Teor. Fiz. This Issue, p. 260 [JETP Lett. **40**, 1037 (1984)].

Translated by Dave Parsons
Edited by S. J. Amoretty