Instability of homogeneous spin precession in superfluid ^{3}He-*A*

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The magnetic-induction signal of ^{3}He-*A* in a uniform magnetic field has been studied. The induction signal falls off in accordance with $I = I_0[1 - A\exp(t/T_F)]$, apparently because of an instability of the homogeneous precession. The results are compared with the instability theory offered by Fomin.

Among the unresolved problems in the physics of superfluid helium 3-*A* are the magnetic-relaxation processes in this system. Experiments carried out by various methods on the restoration of the longitudinal magnetization after excitation of the system by an intense rf pulse[1–4] have shown that the relaxation occurs an order of magnitude more rapidly than predicted by the relaxation theory of Leggett and Takagi.[5] On the other hand, that theory gives a good description of the broadening of the continuous NMR lines, i.e., of the case in which the excursions of the system from equilibrium are small. Leggett and Takagi's theory deals with only a spatially uniform relaxation process. Fomin[6] has shown theoretically that in ^{3}He-*A* a homogeneous precession would be unstable and could decay into large-amplitude spin waves. The resulting spatial inhomogeneity should cause the induction signal to undergo a phase shift after the rf exciting pulse, and it should cause longitudinal-relaxation mechanisms faster than the Leggett-Takagi mechanism to come into play. According to Ref. 7, in the linear approximation the induction signal should fall off

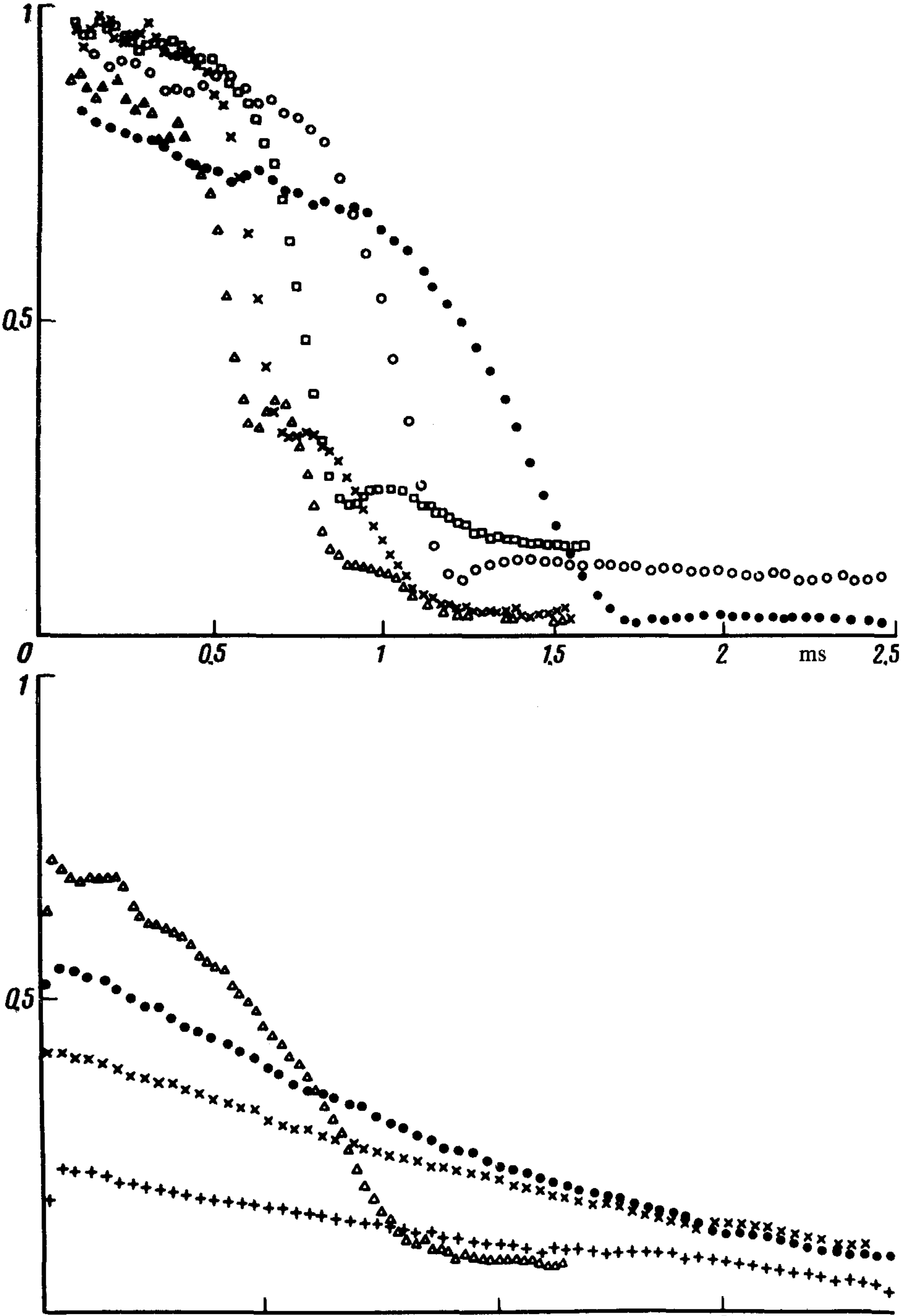

FIG. 1. Time evolution of the intensity of the free-induction signal of ^{3}He-A at the frequency 500 kHz, at $T = 0.82T_c$, and for the following deflection angles: + —15°; × —23°; ● —31°; △ —41° (lower part of figure); ● —52°; ○ —61°; □ —73°; × —82°; △ —100° (upper part).

in accordance with $I = I_0\left(1 - \frac{A\exp t/T_F}{\sqrt{t/T_F}}\right)$, where A is a small nucleating inhomogeneity. In the present experiments we studied the decay of the induction signal in ^{3}He-A.

The experiments were carried out in a copper nuclear-demagnetization cryostat in the temperature interval 2.1–2.7 mK. The test chamber was a cylinder 5 mm in diameter and 13 mm long. The static magnetic field was applied in the direction perpendicular to the axis of the cylinder and was uniform within $\sim 5\times 10^{-5}$ over the cylinder. The rf-field coil was wound around the surface of the cylinder in several sections, in such a manner that the rf field was uniform within 10^{-2} over the greater part of the volume. The ^{3}He pressure in the chamber was 29.3 bar. The experiments were carried out in magnetic fields ~ 77 and ~ 154 Oe, corresponding to NMR frequencies of 250 and 500 kHz. The deviation of the spin system by the rf pulse was determined by the amplitude of the rf field and calibrated with the help of the induction signal in the normal phase of ^{3}He. The length of the rf pulses amounted to eight periods at the frequency 500 kHz and four periods at 250 kHz. With such short pulses, the angles through which the spins are deflected in the normal helium-3 and in the helium-3-A differ by less than 2% at the lowest temperature.[1] The free-induction signal of ^{3}He was amplified, filtered, and recorded at 1024 points by a Datalab 905 digital recorder. The results were then fed to a computer. Figure 1 shows the

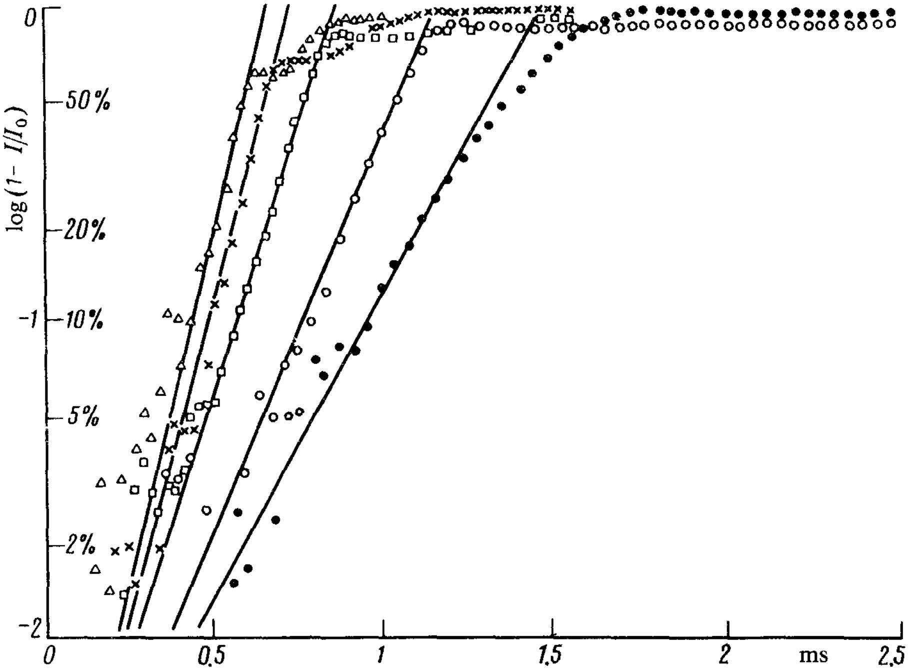

FIG. 2. Time evolution of the intensity of the free-induction signal in ^{3}He-A, expressed as $\log(1 - I/I_0)$. The notation corresponds to the upper part of Fig. 1.

time evolution of the intensity of the induction signal for various deflection angles. At small deflection angles, the induction signal falls off in accordance with $I = I_0 \exp(-t/T_0)$. At larger angles, the decay is qualitatively different. We can clearly see a change in the signs of the curvature of the decay of the signal.

To obtain more-accurate quantitative information on the loss of phase coherence, we corrected the curves in Fig. 1 for the nonuniformity of the external and rf fields. The resulting curves of the decay of the induction signal agree quantitatively with the Leggett-Takagi theory for deflection angles $\lesssim 30°$ over the entire ranges of the temperature and the field used experimentally.

For a quantitative comparison of the experimental decay of the induction signal with the Fomin theory[7] for large deflection angles, we show the results in Fig. 2 as a plot of the time evolution of $\log(1 - I/I_0)$, where I_0 is the signal level at the first experimental points [for the deflection angle $\phi = 52°$, we use as I_0 the level at $t = 0.3$ ms, since there is a clearly defined additional decay of the signal of the $\exp(-t/T)$ type]. These particular coordinates were chosen because at $t \gtrsim 3T_F$ the square-root dependence in the coefficient of the exponential function can be ignored. We see from Fig. 2 that the experimental data correspond to the decay of the induction signal during the onset of an instability for the I range from 5% to 50%. At $\Delta I/I_0 < 5\%$, the scatter in the experimental points becomes very large in these coordinates. The instability should eventually be stopped by an increase of the gradient energy. We may be seeing this limitation in the final part of the induction signal. Here the induction signal falls slowly, and we can usually see some characteristic beats, which arise at $I/I_0 \lesssim 0.2$.

Most of the decay of the induction signals can thus be described by the law $I = I_0(1 - A \exp t/T_F)$. We studied A and $1/T_F$ as functions of the external magnetic field, the temperature, and the deflection angle of the spin system. The quantity A is not found accurately; it lies in the range 10^{-3}–10^{-5}. Figure 3 shows $1/T_F$ vs the

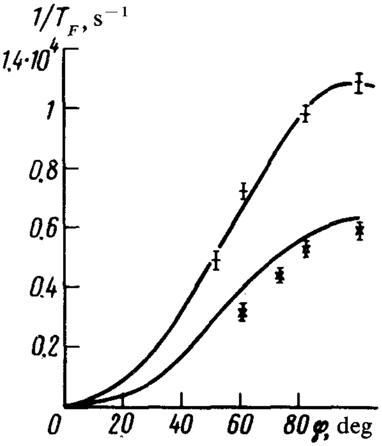

FIG. 3. Instability growth rate vs the spin deflection angle at the frequency 500 kHz. † $T = 0.88T_c$; ‡ $T = 0.9T_c$.

angle through which the spins are deflected by the rf pluse. The solid curve in this figure is drawn in proportion to Eq. (6) of Ref. 7. The instability growth rate $1/T_F$ is proportional to Ω_A^2 and inversely proportional to ω, where Ω_A is the frequency of the longitudinal oscillation mode in ^{3}He-A, which is determined by the temperature, while ω is the Larmor frequency. This behavior was tested over the temperature range (0.94–0.76) T_c at NMR frequencies of 250–500 kHz. The instability growth rate thus depends on the spin deflection angle, the temperature, and the magnetic field, as predicted by the Fomin theory. On the other hand, the growth rate is several times smaller than predicted by this theory. One possible reason for this discrepancy is that the initial nonuniformity of A in the actual test chamber depends strongly on the wave vector K because of the boundary conditions. As a result, an instability with a smaller growth rate but a much larger value of A may dominate the decay of the induction signal. We should also point out that Fomin's theory is derived for the initial stage of the instability, whereas the experimental data were obtained for a region in which the instability was causing an important phase change in the induction signal.

This behavior of the phase change in the induction signal suggests an instability of the homogeneous precession in ^{3}He-A and the development of a spatial texture, which should in turn accelerate the longitudinal relaxation in the ^{3}He-A. We are deeply indebted to P. L. Kapitsa for support and for constant interest in this study, to I. A. Fomin for a close collaboration, to S. M. Elagin for assistance in the experiments, to V. N. Kirillov for developing the computer interface for the experimental apparatus, and to Yu. V. Karpushin for fabricating some of the custom electronics.

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