Torsional vibrations of a domain with uniform magnetization precession in ^{3}He-B

Yu. M. Bun'kov, V. V. Dmitriev, and Yu. M. Mukharskiĭ
Institute of Physical Problems, Academy of Sciences of the USSR

(Submitted 24 December 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 3, 131–134 (10 February 1986)

Oscillations in the amplitude and phase of a long-lived induction signal in ^{3}He-B have been detected experimentally and studied. These oscillations are identified with torsional vibrations of a dynamic magnetic domain which result from oscillations of a superfluid spin current.

The long-lived induction signal which arises in ^{3}He-B after the completion of an rf pulse has been shown in several studies[1,2] to be due to breakup of the ^{3}He sample into two domains, in one of which the magnetization is at equilibrium, while in the other the magnetization precesses in a spatially uniform manner (a dynamic magnetic domain). The arrangement of domains is determined by the direction of the magnetic field gradient. The reason for the uniformity of the magnetization precession in a dynamic magnetic domain is the spatial variation of the Larmor precession frequency is offset by a dipole-dipole frequency shift which arises at magnetization deviation angles β greater than 104°. The distribution $\beta(z)$ is formed and maintained by a superfluid spin current whose magnetization transport is determined primarily by the spatial gradient of the magnetization precession phase,[2] $\partial\alpha(z)/\partial z$. It is natural to expect that when a dynamic magnetic domain is driven from equilibrium spatial oscillations of α and β should arise; the modes of the oscillations were calculated in Ref. 3. In the present letter we report an experimental study of these oscillations.

The experiments are carried out in the chamber described in Ref. 1 at temperatures down to 0.8 mK, at a pressure of 20 bar, in an external magnetic field of 142 Oe. The first rf pulse deflects the magnetization in ^{3}He-B through an angle of approximately 104°. The induction signal is received by a small receiving coil, whose sensitive region is near the edge of the experimental cell. The magnetic field gradient is directed in such a way that the dynamic magnetic domain is formed in the sensitivity region of this coil. After the dynamic magnetic domain is formed, it decreases in size over time because of magnetic relaxation by the Leggett-Takagi mechanism and because of spin diffusion across a domain wall.[1] The amplitude of the induction signal is determined by the size of the dynamic magnetic domain and the sensitivity distribution of the receiving coil. Comparison of the theoretical time evolution of the parameters of the signal with the experimental results, found by the method of Ref. 1, allows us to determine the size of the dynamic magnetic domain. Figure 1 shows some typical results on the amplitude and frequency of the long-lived induction signal as functions of the time, along with corresponding theoretical curves. In the amplitude dependence we have also made a correction for the change in the angle α along the dynamic magnetic domain (this correction is important in the initial part of the signal):

$$\alpha(z) = \alpha(0) + \frac{\tau_{LT}}{8c^2}\gamma^3 H (\nabla H)^2 \left(\frac{z^4}{4} + (L - z)L^3\right), \qquad (1)$$

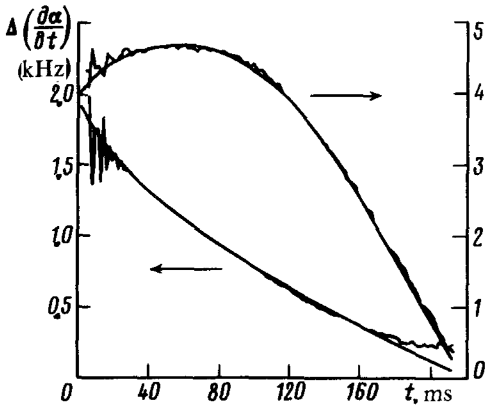

FIG. 1. Intensity (I) and change [$\Delta(\partial\alpha/\partial t)$] in the frequency of the long-lived induction signal versus the time for $T = 0.52T_c$ and $\nabla H = 0.75$ Oe/cm. The smooth curves are theoretical.

where L is the length of the dynamic magnetic domain, τ is a scale time of the Leggett-Takagi relaxation, estimated from Ref. 4, and c is the velocity of the spin waves, estimated from Ref. 5. The reason for the z dependence of α is that the Leggett-Takagi relaxation occurs in the interior of the dynamic magnetic domain. As a result, a superfluid spin current flows out of the interior of the dynamic magnetic domain toward the domain wall, so that there is a "twisting" of α. The vibrations of the dynamic magnetic domain can be seen well in the course of its formation (Fig. 1). For a detailed study of these vibrations, during the observation of the long-lived induction signal, we applied a weak rf pulse to the system. This pulse caused an additional deflection of the magnetization through an angle $\sim 5°$; this deflection drove the distributions of the angles α and β from equilibrium. The phase of the rf pulse was synchronized with the phase of the induction signal. The inset in Fig. 2 shows some typical results on the oscillations of the amplitude and phase of the induction signal after the application of the additional pulse. Also shown here is the dependence of the oscillation period on the thickness of the dynamic magnetic domain for various values of the magnetic field gradient. It turns out that this dependence corresponds to the tortional-vibration mode studied in Ref. 3. The relation between the frequency and amplitude modulations of the induction signal corresponds to the same mode: The amplitude modulation is $\pi/2$ out of phase with the frequency modulation and is noticeable only in high magnetic field gradients, i.e., only when the twisting of α is important.

According to Ref. 3, in a coordinate system which is rotating at the precession frequency of the dynamic magnetic domain, the torsional vibrations constitute a standing wave of spatial variations in the angles α and β. The spin current cannot flow across the wall of the test cell; i.e., we have $\partial\alpha/\partial z = 0$ at this wall,[2] so that a node of the oscillations in the spin current and an antinode of the α vibrations form. As was shown in Ref. 3, the boundary conditions at a domain wall lead to a node in the α vibrations and an antinode in the oscillations of the spin current. Consequently, the fundamental mode of the torsional vibrations of the dynamic magnetic domain corresponds to the case in which the length of the domain is a quarter of the wavelength. We thus have the following expression for the vibration frequency[3]:

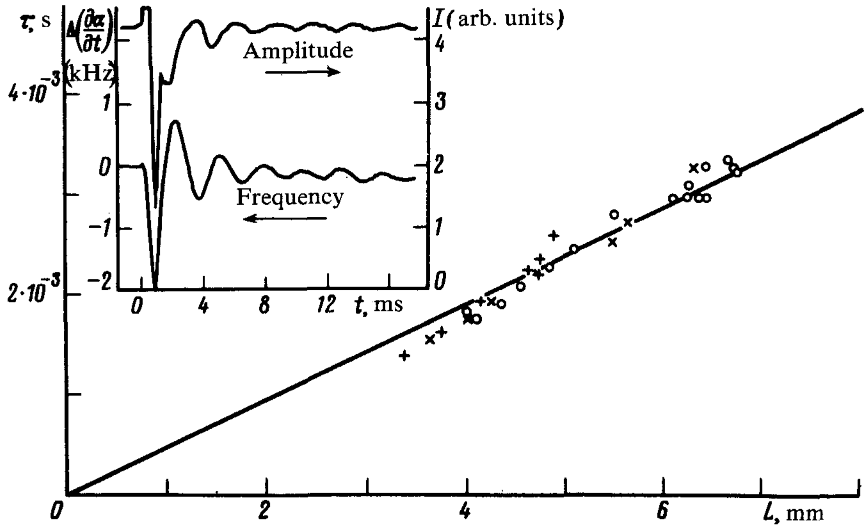

FIG. 2. Dependence of the period (τ) of the vibrations of the dynamic magnetic domain on the length of the domain for $T = 0.51T_c$. ○—$\nabla H = 0.26$ Oe/cm; ×—$\nabla H = 0.75$ Oe/cm; +—$\nabla H = 1.25$ Oe/cm. The inset shows the oscillations in the amplitude (I) and the frequency ($\partial\alpha/\partial t$) of the induction signal upon the excitation of a dynamic magnetic domain 5.6 mm long by a weak rf pulse ($\nabla H = 0.75$ Oe/cm).

$$\omega = \frac{c}{4L}\sqrt{\frac{\Omega_B^2}{\Omega_B^2 + \frac{3}{8}\gamma^2 H^2}}\ ;\ \text{where } c^2 = \frac{5c_\perp^2 - c_\parallel^2}{4}\ , \tag{2}$$

where Ω_B is the Leggett frequency. Since ω and L are known, we can calculate the velocity of the spin waves. The spin-wave velocities which we find by this experimental method are shown in Fig. 3; the solid line shows the dependence $c = 1700\sqrt{1 - T/T_c}$ (cm/s). Our results can be compared with the velocity (s) of spin waves found in measurements in Ref. 5 for a pressure of 35 bar. If we assume that the relations[2]

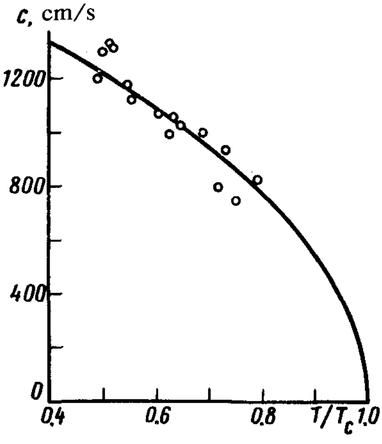

FIG. 3. Spin-wave velocity (c) in ^{3}He-B calculated from the dependence of the period of the torsional vibrations on the length of the dynamic magnetic domain.

$s = c_{\parallel}/\sqrt{2}$ and $c_{\perp}^2 = (3/4)c_{\parallel}^2$ (which are valid near T_c) hold, and if c varies in proportion to the Fermi velocity upon a change in the pressure, then an estimate from the data of Ref. 5 for a pressure of 20 bar leads to the dependence $c = 1540\sqrt{1 - T/T_c}$, in agreement with our results.

We note in conclusion that the experimental points in plots of the type in Fig. 2 tend to lie on a line which does not pass through the origin. This effect may be due to the finite thickness (λ) of the domain wall. In addition to the core of the wall, which is linked with the calibration of the dimensions of the dynamic magnetic domain, there is another special point, determined by the condition $\beta = 104°$, which lies at a distance of 3λ from the core of the wall.[2] Since the scale size of the wall (λ) is 0.2 mm, the experimental data apparently indicate that the node of the α vibrations is associated with this point, rather than with the center of the wall. The correction for this effect reduces our experimental values of c by about 10%.

We wish to thank A. S. Borovik-Romanov for useful discussions of these results and several valuable comments, I. A. Fomin for many stimulating discussions, and K. Flachbart for participation in some of the experiments.

[1] A. S. Borovik-Romanov, Yu. M. Bun'kov, V. V. Dmitriev, Yu. M. Mukharskiĭ, and K. Flakhbart, Zh. Eksp. Teor. Fiz. **88**, 2025 (1985) [Sov. Phys. JETP **61**, 1199 (1985)].
[2] I. A. Fomin, Zh. Eksp. Teor. Fiz. **88**, 2039 (1985) [Sov. Phys. JETP **61**, 1207 (1985)].
[3] I. A. Fomin, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 134 (1986) [JETP Lett. **43**, No. 3 (1986)].
[4] G. Eska, K. Neumaier, W. Shoepe, K. Uhlig, and W. Wiedermann, Phys. Lett. **87A**, 311 (1982).
[5] D. D. Osheroff, Physica **90B**, 20 (1977).

Translated by Dave Parsons