Coherently precessing magnetization structure in normal ^{3}He in pulsed NMR

V. V. Dmitriev, S. R. Zakazov, and V. V. Moroz
P. L. Kapitsa Institute of Physical Problems, 117334 Moscow, Russia

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Pulsed NMR experiments have been carried out in liquid ^{3}He at temperatures below 10 mK. At sufficiently low temperatures, the duration of the induction signal is significantly longer than would be expected on the basis of the nonuniformity of the external magnetic field. Comparison of the experimental results with theory and numerical simulations indicates that the discrepancy stems from the formation of a coherently precessing, two-domain spin structure. The conditions required for the formation of such a structure are determined. © *1995 American Institute of Physics.*

The spin dynamics of a normal Fermi liquid is described by Leggett's equations,[1] which are, in a first approximation,

$$\frac{\partial \mathbf{M}}{\partial t}+\frac{\partial \mathbf{J}_i}{\partial x_i}=\mathbf{M}\times\boldsymbol{\omega}, \tag{1}$$

$$\mathbf{J}_i=\frac{D_0}{1+\mu^2M^2}\left\{\frac{\partial \mathbf{M}}{\partial x_i}+\mu\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial x_i}+\mu^2\left(\mathbf{M}\frac{\partial \mathbf{M}}{\partial x_i}\right)\mathbf{M}\right\}, \tag{2}$$

where

$$\mu=\frac{\omega\kappa\tau}{1+F_1^a/3},\quad \kappa=\frac{F_1^a/3-F_0^a}{1+F_0^a},\quad D_0=\tfrac{1}{3}v_F^2(1+F_0^a)\tau,$$

F_0^a and F_1^a are Fermi parameters, τ is the quasiparticle collision time, $\mathbf{M}$ is the magnetization divided by its equilibrium value, D_0 is the spin-diffusion coefficient, v_F is the Fermi velocity, $\omega=\gamma H$ is the NMR frequency, γ is the gyromagnetic ratio, and H is the magnetic field.

The first term in braces (curly brackets) in Eq. (2) describes ordinary spin diffusion. It determines the spin dynamics at high temperatures, where μ is small. In the low-temperature limit, the second and term terms become significant in the spin dynamics. For example, they lead to the possibility of an excitation of spin waves in normal ^{3}He and in ^{3}He–^{4}He solutions.[2,3] Induction signals lasting longer than would be expect on the basis of the nonuniformity of the magnetic field were recently observed[4,5] in some pulsed NMR experiments on ^{3}He–^{4}He solutions. In an effort to explain these signals, some numerical simulations were carried out. They showed that the flow of Fermi-liquid spin currents in a field with a uniform gradient after the application of a deflecting pulse could give rise to a spin structure consisting of two domains. The magnetization in one of the domains would be oriented along the external magnetic field, while that in the other

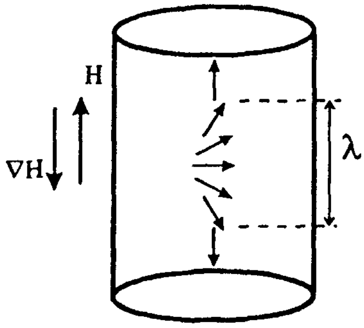

FIG. 1. Precessing two-domain structure in a closed cell. The arrows show the distribution of magnetization vectors.

would be in the opposite direction. The domains would be separated by a wall in which the magnetization would rotate smoothly from 0 to 180°. Although the geometry of the experimental cells used in Refs. 4 and 5 did not allow a quantitative comparison with the results of the simulation, the basic properties of the induction signals found agreed with the calculations. An analytic solution of Leggett's equations was recently found. This solution describes a steady-state precession of the magnetization in a nonuniform external field in the low-temperature limit.[6,7] That solution corresponds to the two-domain structure described above. Despite the gradient of the external field, the free precession of spins occurs with the same phase and with a frequency corresponding to the Larmor value at the middle of the domain wall (Fig. 1). The characteristic thickness of the wall under these conditions is given by

$$\lambda^3=\frac{u^2}{\kappa M\omega\nabla\omega}, \tag{3}$$

where

$$u^2=\tfrac{1}{3}v_F^2(1+F_0^a)(1+F_1^a/3),\quad \nabla\omega=\gamma\nabla H.$$

The coherent precession of a domain wall is sustained by the flow of spin currents, which transport transverse components of the spin. The mechanism for the formation of a two-domain structure can be seen in the following simple model. A Fermi liquid is in a closed cell in a magnetic field (directed along the z axis) with a uniform gradient. The condition $\mu \gg 1$ holds; we can thus ignore the first term in Eq. (2). If the absolute value of the magnetization is uniform throughout the cell, the third term in (2) is zero. Furthermore, this term prevents a growth of spatial variations in the absolute value of the magnetization; in the collisionless limit it keeps this absolute value uniform over volume. If the magnetization of the sample is deflected through an angle β and undergoes a free precession, the gradient of the Larmor frequency of the precession will cause a gradient of the precession phase α to arise and to increase in the interior of the sample. In this case the second term in (2) leads to the onset of a current of the longitudinal component of the magnetization along the z axis. If β is uniform along the sample, this current is

$$J_z^z=\frac{\mu D_0 M^2\sin^2\beta}{1+\mu^2M^2}\nabla\alpha. \tag{4}$$

This current redistributes the longitudinal magnetization: The latter increases at one end of the sample and decreases at the other. The result would presumably be a structure consisting of two domains with oppositely directed magnetizations.

We recently carried out some pulsed NMR experiments[8] with a saturated ^{3}He–^{4}He solution in cells of various configurations at temperatures on the order of 1 mK. The experimental results turned out to be in good quantitative agreement with the numerical simulations. The results of both the experiments and the simulations indicate the formation of a two-domain structure. Because this structure forms, the typical lifetime of the induction signal is considerably longer than that which would be expected on the basis of the existing nonuniformity of the external magnetic field. At low temperatures the longitudinal magnetic relaxation in ^{3}He–^{4}He solutions (as in normal ^{3}He) is slight and occurs at the cell walls. In this case the primary relaxation mechanism affecting the lifetime of the two-domain structure (and, correspondingly, the induction signal) is a relaxation associated with ordinary spin diffusion [the first term in Eq. (2)]. This mechanism leads to a progressive decrease, to zero, in the absolute value of the magnetization over the volume of the cell (of length L), in accordance with[6,7]

$$\frac{d}{dt}[M]^{5/3} \approx \frac{3.9}{L\tau}(1+F_1^a/3)\left\{\frac{u^4\nabla\omega}{\kappa^5\omega^5}\right\}^{1/3}. \tag{5}$$

The Fermi-liquid effects which lead to the formation of the two-domain structure are determined by the absolute value of μ. For a saturated ^{3}He–^{4}He solution at zero pressure we would have $F_0^a=0.01$, $F_1^a=0.144$, $\tau T^2=3.47\times 10^{-11}$ s·K^2 (Ref. 4), and, correspondingly, $\mu T^2=1.26\times 10^{-12}\omega$. For normal ^{3}He at 0 bar we would have $F_0^a=-0.695$, $F_1^a=-0.6$, $\tau T^2=4.11\times 10^{-13}$ s·K^2 (Refs. 9–11), and, correspondingly, $\mu T^2=0.84\times 10^{-12}\omega$. Accordingly, even in magnetic fields on the order of 200–300 Oe and at temperatures on the order of 1 mK, Fermi-liquid spin currents can play a governing role in normal ^{3}He, as in a saturated ^{3}He–^{4}He solution; they can lead to the formation of a two-domain structure of the magnetization. Nevertheless, despite the numerous studies involving pulsed NMR experiments in normal ^{3}He, the literature has no report of the observation of effects associated with the formation of a two-domain structure. Our purposes in the present study were to identify the necessary conditions for the formation of a two-domain structure and to observe effects stemming from its onset.

We carried out numerical simulations of pulsed NMR in normal ^{3}He for some typical experimental conditions (pressure of 0 bar, H = 100–1000 Oe, ∇H = 0.1–1 Oe/cm, T = 1–20 mK). We solved the complete system of Leggett's equations for the 1D case; i.e., we assumed that the system was uniform in the x–y plane. The external magnetic field and also its gradient were directed along the z axis. As boundary conditions at the ends of the cell we required that there be no spin current; i.e., we assumed that the cell was closed. In the calculations we used a standard program for solving partial differential equations from the ACM library,[12] obtained at the Computation Center of the Institute of Physical Problems, Russian Academy of Sciences. As initial conditions we chose a deflection of the magnetization through a certain angle, uniform over the cell. The computer calculated the distributions of the various components of the magnetization and the spin current along the z axis at various times. For convenience in comparing the results of these calculations with experiment, we also calculated the total transverse

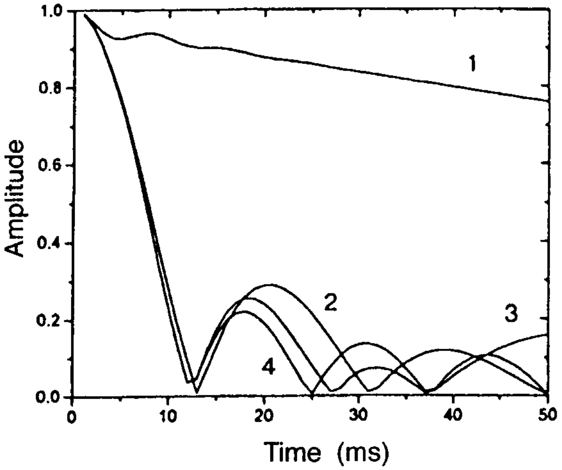

FIG. 2. Time evolution of the amplitude of the free-induction signal after an initial deflection of the magnetization through an angle of 90° (these are results of a numerical simulation). Cell height of 0.62 mm, ∇H=0.4 Oe/cm: 1—T=0.93 mK; 2—10 mK. Cell height of 4.96 mm, ∇H= 0.05 Oe/cm: 3—0.93 mK; 4—T=10 mK.

component of the magnetization of the ^{3}He sample at each instant. In other words, we actually calculated the amplitude of the induction signal induced by the precessing spins. It turned out that the results depend very strongly on the ratio of the height (along the z axis) of the test cell (L) to the characteristic thickness of the domain wall, given by Eq. (3). The domains first begin to form near the ends of the cell and then "sprouted" into the interior. If $L/\lambda \gg 1$, the gradient of the Larmor frequency along the z axis quickly causes the phase of the precession along the cell to change by more than 2π. The gradients of the magnetization components which arise in the process at a nonzero temperature (this temperature was set above the temperature at which ^{3}He goes into its superfluid state,[11] T_c =0.93 mK) sharply accelerate the relaxation of the absolute value of the magnetization. As a result, the two-domain structure forms when the absolute value of the magnetization is essentially zero. In this case the time scale for the decay of the induction signal is essentially independent of the temperature; i.e., it is the same as the time found from the standard condition for complete phase relaxation of noninteracting spins:

$$\tau^* = \frac{2\pi}{L\nabla\omega}. \tag{6}$$

If, on the other hand, L/λ is on the order of one, the two-domain structure forms before the absolute value of the magnetization relaxes. If a structure has formed, then the gradients of the magnetization are relatively small and are concentrated near the wall. At a sufficiently low temperature, the rate of relaxation of the absolute value of the magnetization is thus small [see Eq. (5)]. Figure 2 shows the time evolution of the amplitude of the induction signal after an initial deflection of the magnetization through 90°, calculated for various values of the parameters ∇H, T, and L. We took the value of $L\nabla H$ to be the same for all the curves, so the signal decay time (the time taken to reach the first minimum) should be given by Eq. (6) in the high-temperature limit and should be $\approx$12.4 ms. We see that at 10 mK the decay times for the two different values of L are indeed given by Eq. (6) (curves 2 and 4 in Fig. 2). In addition, if the height of the cell is large (L = 4.96 mm, L/λ = 8), the shape of the induction signal is essentially indepen-

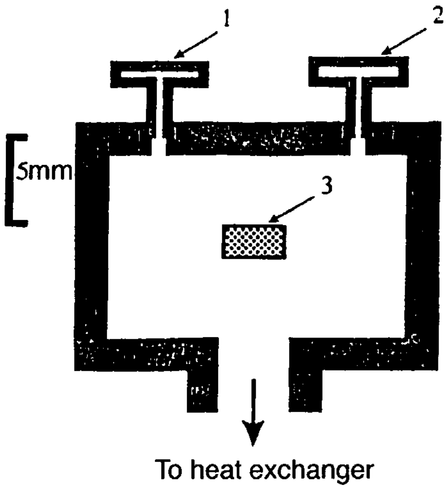

FIG. 3. Schematic diagram of the test chamber. 1,2—Experimental cells; 3—sensor of NMR thermometer.

dent of the temperature (curves 3 and 4). As we know, long cells were used in all previous experiments in which an induction signal from normal ^{3}He was observed; i.e., the condition $L/\lambda \gg 1$ held. It is apparently for this reason that no significant changes were observed in the induction signal as the temperature was lowered. If one instead uses a short cell (L = 0.62 mm, $L/\lambda = 2$), then the shape of the induction signal should depend strongly on the temperature, as can be seen from Fig. 2 (curves 1 and 2). At high temperatures, where Fermi-liquid effects are small, the decay of the induction signal is again described well by Eq. (6), but at low temperatures a two-domain structure forms in the cell, and the induction signal falls off much more slowly.

To test the conclusions drawn from the numerical simulations, we carried out some pulsed NMR experiments in two cylindrical test cells, 5 mm in diameter. The cells were made from Stycast-1266 epoxy resin and differed in height (0.62 and 0.9 mm). The cells were connected by long (4.7-mm), narrow (0.7-mm) channels to the main ^{3}He volume, which was cooled by a heat exchanger. The cells were thus effectively closed (Fig. 3). Each cell was inside a transmitting–receiving NMR coil (not shown in the figure). The experiments were carried out at temperatures below 20 mK, at a pressure of 0 bar, and in a magnetic field of 284 Oe (the NMR frequency is 920 kHz). The magnetic field was directed along the axis of the cells. The temperature was measured with a PLM-3 platinum NMR thermometer, which was calibrated on the basis of the superfluid transition of ^{3}He.

Here is the experimental procedure. As the temperature is raised slowly below T_c at a fixed level of the nonuniformity of the external magnetic field, deflecting rf pulses are applied to the ^{3}He sample. The free-induction signals are measured with a digital storage oscilloscope. Figure 4 shows some of the signals found from the cell 0.62 mm high at various temperatures. We see that the induction signal lasts considerably longer at a low temperature, indicating the formation of a two-domain structure. As a quantitative characteristic of the length of the induction signal we adopted the time over which the signal amplitude drops by a factor of 3. Figure 5 shows the temperature dependence found

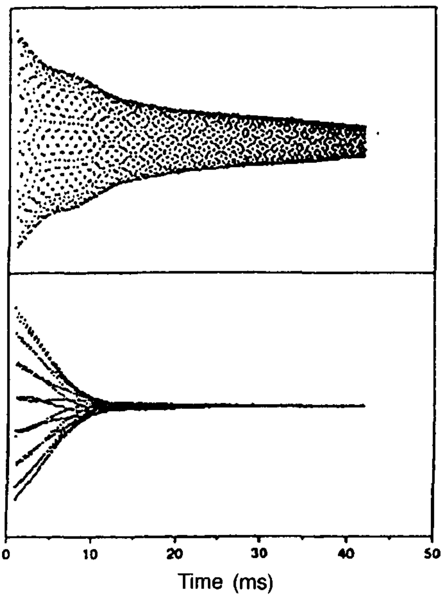

FIG. 4. Time evolution of the free-induction signal after an initial deflection of the magnetization through 90° in a cell 0.62 mm high (experimental). ∇H =0.58 Oe/cm. Top—T=0.94 mK; bottom—T=3.1 mK.

experimentally for the decay time of the induction signal in the two cells, for a field gradient of 0.41 Oe/cm. We see that the elongation of the induction signal at low temperatures is more apparent for the thinner cell, i.e., for the case in which the parameter L/λ is smaller. The durations of the induction signal found experimentally at temperatures on the order of 1 mK were smaller by a factor of 1.5 or 2 than we expected on the basis of the numerical simulations. The apparent reason for this discrepancy is that the axes of the cells were not parallel to the external magnetic field; i.e., the actual conditions

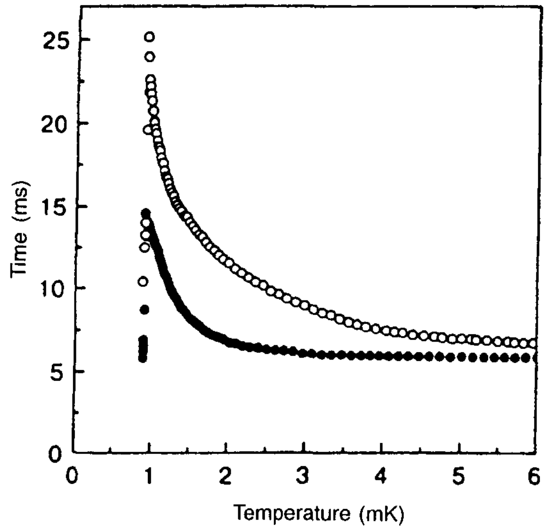

FIG. 5. Temperature dependence of the decay time of the induction signal. The initial deflection was 90°. ∇H = 0.41 Oe/cm. ○—Cell height of 0.62 mm; ●—0.9 mm.

did not correspond to the 1D case. From the high-temperature measurements we estimated the angle between the cell axes and **H** to be $\approx 1-2^\circ$. On the whole, however, our results are described satisfactorily by the theory, and they support the suggestion that a coherently precessing structure can form in normal ^{3}He.

As the temperature is lowered below T_c, the induction signal quickly becomes shorter, apparently because of a magnetic relaxation by the Leggett–Takagi mechanism[13] in superfluid ^{3}He. Nevertheless, the length of the induction signal in the immediate vicinity of the superfluid transition temperature is greater than at high temperatures (Fig. 5). This result indicates that Fermi-liquid spin currents continue to have a significant effect on the spin dynamics even in superfluid ^{3}He (at least near T_c).

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