Method of achieving a two-domain magnetization precession in an antiferromagnetic solid ^{3}He

I. A. Fomin and D. V. Shopova
L. D. Landau Institute of Theoretical Physics, Academy of Sciences of the USSR

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In the antiferromagnetic phase of solid ^{3}He at certain directions of the magnetic field with respect to the anisotropy axis of the magnetic structure a spatially uniform magnetization precession may become a two-domain precession similar to the one observed previously in a superfluid ^{3}He-*B*.

Borovik-Romanov *et al.*[1] and Fomin[2] have recently shown that a spatially inhomogeneous, precessing structure forms in a superfluid ^{3}He-*B* when the magnetization is deflected from the equilibrium position at a finite angle in a slightly nonuniform magnetic field at $\mathbf{H}_0$. This structure consists of two domains. In one domain the magnetization is parallel to $\mathbf{H}_0$ and in the other it is deflected from $\mathbf{H}_0$ by an angle $\beta_0 = \arccos(-1/4)$. A structure of this sort forms because the dipole energy U_D of ^{3}He-*B*, as a function of two of its arguments $\Phi = \alpha + \gamma$ and $u = \cos\beta$ (α, β, γ are Euler's angles which determine the orientation of the order parameter), has a line of nonisolated singularities, i.e., such singularities for which $\partial U_D/\partial\Phi = 0$ and $\partial U_D/$

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$\partial u = 0$, and a determinant $[\partial^2 U_D/\partial\Phi^2)(\partial^2 U_D/\partial u^2)] - (\partial^2 U_D/\partial\Phi\partial u)^2 = 0$. A similar situation may occur in an antiferromagnetic phase of a solid ^{3}He if it is assumed that its magnetic dynamics can be described by equations proposed by Osheroff, Cross, and Fisher[3] (below referred to as OCF). Except for the sign in front of the dipole term, these equations are the same as the Leggett equations for ^{3}He-A. This circumstance makes it possible to take an average over fast motions in the analysis of the motion of magnetization in fields for which the Larmor frequency ω_L is high in comparison with the frequency of the antiferromagnetic resonance Ω in a zero field.[4] The effect of a specific magnetic structure on the motion of magnetization at $\omega_L \gg \Omega$ is determined by the dipole energy V_D which is averaged over the precession and which in the case under consideration can be written as follows:

$$V_D = \frac{\Omega^2}{16}[2(1+u^2) + 2(1-3u^2)\cos^2\theta + (1+u)^2\sin^2\theta\cos 2\Phi] . \tag{1}$$

V_D depends on the angle θ between $\mathbf{H}_0$ and the direction l which determines the spatial orientation of the proposed OCF structure. For $\cos^2\theta = 1/5$ the energy V_D has a line of nonisolated singularities $\theta = \pi/2$ (the line $\Phi = 0$ clearly corresponds to unstable states). An appropriate choice of the precession-frequency shift causes $\partial V_D/\partial u$ to vanish on this line. Using arguments similar to those[2] applied to ^{3}He-B, we find that for $\cos^2\theta = 1/5$ even a weak Larmor-frequency gradient leads to a decay of an initially uniform magnetization precession into two domains. The magnetization in a domain situated in stronger fields is parallel to the field and the magnetization in a domain situated in weaker fields is antiparallel to the field.

To determine the shape of the domain wall and to trace the transition from a spatially uniform precession to a two-domain precession due to a change in the angle θ, we will set $\cos^2\theta = 1/5 + \kappa (\kappa \ll 1)$ and single out in the dipole energy the terms proportional to κ, i.e., $V_D = V_D^{(0)} + \kappa w$. As in the case of ^{3}He-B, the steady-state precession corresponds to the extremal values of the functional

$$F = \int [\mathcal{H}^{(0)} + \omega_p^{(0)} P + \mu P + G_\nabla - S_z(z\nabla\omega_L) + \kappa w] dz . \tag{2}$$

Here $\mathcal{H}^{(0)}$ is the spatially uniform part of the Hamiltonian, and G_∇ is the average gradient energy which corresponds to the energy found previously[5] for ^{3}He-A. The Larmor frequency is assumed to vary linearly in the z direction parallel to $\mathbf{H}_0$. We take the origin to be at the center of the sample which is assumed to be cylindrical and to have a single domain. The Lagrangian multiplier ω_p which determines the precession frequency is divided into two parts, $\omega_p^{(0)}$ and μ, in such a way that $\omega_p^{(0)}$ corresponds to the uniform-precession frequency at $\kappa = 0$ (p is the canonical momentum which is conjugate to the angle α). The last four terms within the integral in (2) are small to the extent that κ or $L\nabla\omega_L/\omega_L$ is small, where L is the linear dimension of the sample. This circumstance makes it possible, as in the case of ^{3}He-B to initially minimize the first two terms, which gives us $\cos\Phi = \pi/2$, and then to minimize the remaining part of the functional F for a given Φ. From the stipulation that there be no spin currents in the steady state, we find $\alpha = \text{const}$, and after minimizing over β, we find

$$\frac{d^2\beta}{d\zeta^2} - \tau\sin\beta\cos\beta - \zeta\sin\beta = 0 . \tag{3}$$

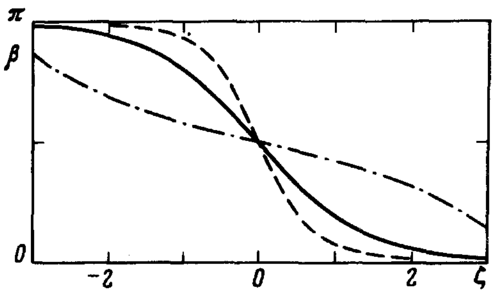

FIG. 1. The shape of the domain wall for various values of the parameter τ. Dot-dashed curve—$\tau = -4$; solid curve—$\tau = 0$; dashed curve—$\tau = 4$.

Here $\zeta = (z - z_0)/\lambda$, $z_0 = (\mu/\nabla\omega_L) + (\kappa\Omega^2/8\omega_L\nabla\omega_L$, and $\lambda = [(c_\parallel^2 + 4c_\perp^2)/10\omega_L\nabla\omega_L]^{1/3}$ is the characteristic length specified by the nonuniformity of the magnetic field, $c_\parallel$ and $c_\perp$ are the velocities of the spin waves directed parallel and perpendicular to l, and $\tau = 25\kappa\Omega^2\lambda^2/4(c_\parallel^2\ 4c_\perp^2)$. Although the Lagrangian multiplier μ is not explicitly included in Eq. (3), it does determine the position of the boundaries. To determine μ and the functional dependence $\beta(z)$ in the sample, we must first solve Eq. (3) which satisfies the conditions $\beta \to 0$ as $\zeta \to \infty$ and $\beta \to \pi$ as $\zeta \to -\infty$, and then select an interval $[\zeta_0 - (L/\lambda), \zeta_0 + (L/\lambda)]$ in such a way that $\int P d\zeta$ within this interval would be equal to the given initial value. We would then find $z_0 = -\lambda\zeta_0$, μ, and the precession frequency $\omega_L(z_0) + (1 - 5\kappa/4)\Omega^2/10$.

The particular way in which β changes in the sample depends on the sign of τ and on the relationship between τ and L/λ. At $\tau < 0$ and $|\tau| \gg L/\lambda$ the precession can be said to be nearly uniform. At $\tau = 0$ we have a domain wall of thickness on the order of λ which separates the regions with $\beta = 0$ from the regions with $\beta = \pi$ and which is similar to the domain wall in ^{3}He-B. For typical values of $\omega_L \simeq 2\times 10^7$ rad/s, $\nabla\omega_L \approx 2\times 10^4$ rad/s·cm, and $c^2 \simeq 8$ cm/s we find $\lambda \simeq 5\times 10^{-4}$ cm. With a further increase in τ, a transition occurs to the instability region of spatially uniform precession.[6] Because of the presence of an external inhomogeneity, this transition occurs smoothly—the shape and thickness of the domain wall change with increasing τ (Fig. 1). At $\tau \gg L/\lambda$ the last term in Eq. (4) can be dropped. As a result, we find a familiar equation, whose solution is

$$\cos\beta = \tanh\left[(z - z_0)\frac{\sqrt{\tau}}{\lambda}\right] ;$$

i.e., we have a domain wall of thickness $\sim\lambda/\sqrt{\tau} = [(c_\parallel^2 + 4c_\perp^2)/\kappa]^{1/2}(2/5\Omega)$ $\sim 10^{-6}/\sqrt{\kappa}$ cm.

The arguments presented above apply to a single domain and cannot be applied directly to the available experimental results[7] which were obtained for polydomain samples. The study of the "engagement" and "disengagement" of the uniform-precession instability is important in order to understand the magnetization relaxation in an antiferromagnetic ^{3}He and in a superfluid ^{3}He-A. An attempt should therefore be made, on the one hand, to obtain single-domain samples and to carry out measurements with these samples similar to those in Ref. 7 and, on the other hand, to describe theoretically the transition to a spatially nonuniform precession, with allowance for the domain structure of the samples. Under these conditions, the analysis performed by us here can be exploited, after appropriate modifications, to describe the processes that occur in single domains.

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