Pulsed NMR in ^{3}He–B for a non-Leggett configuration

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An explanation is offered for a threshold effect observed under pulsed-NMR conditions in ^{3}He–B between parallel plates.

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Borovik-Romanov *et al.*[1] recently discovered a new effect in a pulsed-NMR study of ^{3}He–B: An induction signal was observed only when the magnetization was rotated through an angle above a certain threshold. When the induction signal was observed, it was at the the Larmor frequency. The primary difference between the experiment of Ref. 1 and earlier pulsed-NMR experiments[2,3] with ^{3}He–B was that the helium was in a gap between parallel plates which were initially oriented in such a manner that the axis **n** of the order-parameter matrix $R(\mathbf{n}, \theta)$ (θ is the angular position) made an angle $\varphi = \arccos(1/\sqrt{5})$ with the static magnetic field $\mathbf{H}_0$. In other words, the initial configuration was not a Leggett configuration.

Another difference between the experiment of Ref. 1 and the others was that the Larmor frequency $\omega_L = gH_0$ (g is the gyromagnetic ratio) was comparable in magnitude to the longitudinal oscillation frequency Ω. For this reason, the asymptotic methods cannot be used to describe the motion of the magnetization under the experimental conditions of Ref. 1.

In this letter we analyze the magnetization motion under the experimental conditions of Ref. 1 by working from some exact steady-state solutions of the Leggett equations which were found previously.[4,5] We also use a numerical solution of the Leggett-Takagi equations[6] which allows us to study the motion of the magnetization and of the order parameter during the application of the rf deflecting pulse and the subsequent relaxation to one of the steady-state solutions. On the basis of this analysis we offer a theoretical interpretation of the experiment of Ref. 1.

The results of the analysis are conveniently shown graphically as the path traced out by the system in the coordinate system θ, $(\mathbf{n}, \mathbf{H}_0)$, $P = S_Z - S_\zeta$, where S_Z is the projection of **S** on the OZ axis, which is oriented along the initial equilibrium direction of **S**, while S_ζ is the projection of **S** on the movable axis $O\zeta$. The latter axis is obtained from OZ through the action of the matrix $R(\mathbf{n}, \theta)$, which corresponds to the instantaneous configuration of the order parameter. It has been shown elsewhere[7,8] that in the absence of an rf field P is an integral of motion of the Leggett equations for ^{3}He–B.

The steady-state solutions of the Leggett equations for ^{3}He–B are given by equations in terms of the variables θ, $(\mathbf{n}, \mathbf{H}_0)$, P, which are equivalent to the equations derived in Refs. 4 and 5 for other sets of variables. The heavy curves in Fig. 1 show the stable branches of the steady-state solutions. Points L and L' correspond to a Leggett configuration. This is a special configuration because it corresponds to an intersection of two branches of steady-state solutions: the static branch (the arc $L'NL$ in Fig. 1) and

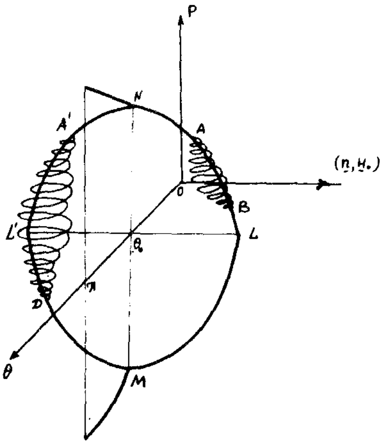

FIG. 1. Points A and A' correspond to possible initial states. The rf pulse causes an image point in this diagram to move downward along a spiral. After the rf pulse, the point continues to move along the spiral, but dissipation causes the spiral to contract toward one of the steady-state solutions. If the pulse length is below the threshold value, the contraction occurs to a static solution (point B), while if the pulse length is above the threshold the contraction occurs to the Brinkman-Smith solution (point D). For clarity, different initial states are shown for these two cases. Here $\theta_0 = \arccos(-1/4)$. (This is a schematic diagram.)

the Brinkman-Smith branch[9] of the solutions (BS, arc LML'), which describe a steady-state precession of the magnetization at the Larmor frequency. The other Points on arc $L'NL$ correspond to various non-Leggett configurations. When the system is excited from the Leggett configuration by an rf pulse which is not too strong, the magnetization and the order parameter move along arc LM over time during the pulse.[8] After the rf field is removed, they lie near one of the BS solutions. For non-Leggett configurations, in contrast, the rf pulse puts the system in a state which is generally far from any steady-state solution. Our numerical solution of the Leggett-Takagi equations showed that under the experimental conditions of Ref. 1 the relaxation occurred to either one of the static solutions or the BS solution, depending on the length of the rf pulse (Fig. 1). Neither of these solutions undergoes any subsequent relaxation according to the theory of Leggett and Takagi. There is a certain particular pulse length for which the system relaxes to a boundary state: a Leggett configuration. This particular pulse length should be regarded as a threshold value, for the following reasons. After the relaxation has been completed, there should be no induction signal if the relaxation has led to a static solution, or it should have the Larmor frequency if the relaxation has led to the BS solution. This is precisely the behavior which was observed in the experiment of Ref. 1. The calculated value of the threshold pulse length is 22 μs for $\omega_L = 2\pi\cdot 500$ kHz, $\Omega = 2\pi\cdot 200$ kHz, and an rf field amplitude $H_1 = 2$ Oe. This prediction agrees well with the pulse length observed experimentally for these conditions.

The only question which requires further discussion is why, in an experiment with a pulse length below the threshold, the induction signal was also missing during the approach to the static solution. The explanation apparently lies in a discrepancy between the actual experimental conditions and the simplified model which we are assuming here. A spatial nonuniformity of the pulsed rf field and a deviation from a perfectly parallel arrangement of the plates would cause the trajectories traced out by the magnetization and the order parameter to be slightly different for different regions in the helium volume. A numerical analysis shows that for the experimental conditions of Ref. 1, and under the assumption $\Gamma_{\parallel} = 0.2\Omega$ in the Leggett-Takagi equations, the trajectories will reach the vicinity of one of the steady-state solutions in a time no greater than ~ 100 μs. If the solution reached is the Brinkman-Smith solution, an initial spread in the trajectories will have essentially no effect on the induction signal, since near the BS solution all the points describe a magnetization precession with the same frequency ω_L. Near the static solutions, in contrast, the precession frequency depends on the particular static solution [see Eq. (2) in Ref. 1]. For this reason, a spread caused by the initial conditions should grow: With a 10% spread in the initial conditions over the helium volume, the phase coherence of the magnetization should be lost completely, i.e., the induction signal should disappear, in a time ≈ 200 μs (the dead time of the electronics in the experiment of Ref. 1).

This analysis thus agrees with the results of Ref. 1. If we adopt a non-Leggett configuration as the initial configuration for pulsed NMR experiments, the relaxation of the magnetization can occur in two qualitatively different ways, depending on the length and strength of the deflecting rf pulse.

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