Tip-Angle-Dependent Magnetic Relaxation in Superfluid ^{3}He

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Using a pulsed superconducting-quantum-interference-device (SQUID) NMR technique, relaxation of the longitudinal magnetization in superfluid ^{3}He has been measured in magnetic fields of 31, 102, 180, and 306 Oe in the pressure range 16–26 bar. It is observed that in both superfluid phases there is a temperature-dependent, well-defined spin-tipping angle, θ_c, for which the relaxation of the magnetization changes from an exponential to a nonexponential behavior.

Recent experiments[1-3] on the relaxation of the longitudinal magnetization of superfluid ^{3}He have shown the existence of some unusual and very interesting relaxation mechanisms. In particular, for ^{3}He-A, Corruccini and Osheroff[2] have observed relaxations of the magnetization which are nearly linear in time while Sager *et al.*[3] have found that very near T_c, in low fields, the *square* of the magnetization recovers linearly in time as predicted by Leggett and Takagi[4,5] (L-T). In ^{3}He-B, strictly exponential relaxation was observed by Corruccini and Osheroff, while near T_c Sager *et al.* observed more complicated nonexponential behavior. In this work, relaxation phenomena in ^{3}He have been studied in static fields of 31, 102, 180, and 306 Oe in the pressure range 16–26 bar using a pulsed superconducting-quantum-interference-device (SQUID) NMR technique.[6] The technique of SQUID NMR is ideally suited for studying relaxation phenomena. Following a single rf pulse that rotates the magnetization through a known angle θ, the recovery of the longitudinal magnetization is continually monitored by the longitudinal SQUID detection coil (coil axis parallel to the static field H_0), independent of dephasing effects. It is found that the relaxation of the longitudinal magnetization of ^{3}He is very similar in the two phases but the exact nature of the recovery process exhibits a striking dependence on the choice of the initial tip angle.

The adiabatic demagnetization cell used for the experiments reported here has been described elsewhere.[7] The ^{3}He measured was contained in a 3-mm-i.d. tower located above the main cell. The static field H_0, parallel to the axis of the tower, was trapped in a 10.9-mm-i.d. Nb tube. The transverse H_1 field was produced by a pair of saddle coils wound on a diameter of 5 mm. Temperatures were determined from 17-Hz mutual-inductance measurements on 10 mg of cerium magnesium nitrate (CMN) located in a second magnetically shielded tower. A provisional absolute scale was obtained with the aid of the phase diagram reported by Wheatley.[8]

Some typical examples of the time dependence of the recovery of the longitudinal magnetization in ^{3}He-B following an rf pulse are shown in Fig. 1. The first trace was obtained following a 90° rotation of the magnetization and most of the recovery of the z component of magnetization occurs exponentially in time. The initial part of the recovery is somewhat slower than the latter

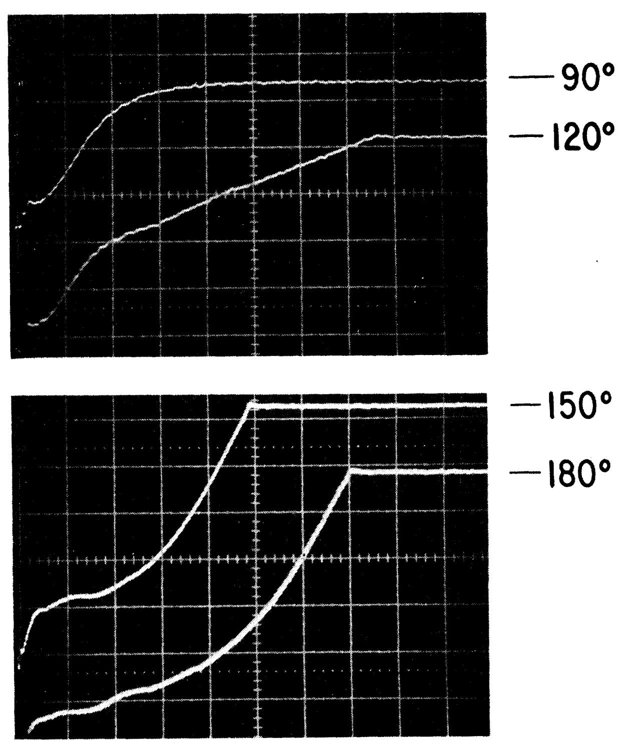

FIG. 1. Four examples of the relaxation of the longitudinal magnetization of superfluid ^{3}He-B, following 90°, 120°, 150°, and 180° rotations of the magnetization, obtained at $T/T_c = 0.967$ in 180 Oe at 21 bar. The time base for the 90° and 120° data was 0.5 msec/cm and for the 150° and 180° data was 2.0 msec/cm.

part as is characteristic of nearly all the exponential relaxation observed in this work. The second trace, obtained following a 120° pulse, is an example of a relaxation process that occurs nearly linearly in time. The initial part of the recovery of the magnetization is very similar to the type of recovery observed in the first trace. Because of a spurious background magnetization and finite electronic recovery time,[7] the first 100–200 μsec of all the magnetization recoveries must be ignored. The third and fourth traces were obtained following 150° and 180° pulses and the latter is an example of a relaxation process where the square of the magnetization relaxes nearly linearly in time. For all the results reported here the width of the rf pulse was approximately 25 cycles and the initial magnetization change agreed with the expected change based on the known rotation angle and dynamic susceptibility[7,8] of ^{3}He to better than 5%, independent of the exact nature of the recovery process. These three types of relaxation processes are also observed in ^{3}He-A.

For both ^{3}He-A and ^{3}He-B there is a fairly well-defined spin-tipping angle, θ_c (generally reproducible to within ± 2%), for which the relaxation process dramatically changes from mainly exponential to nonexponential behavior. Following a rotation of the magnetization by an angle θ, the change in the energy of the spin system is[5] $(\Delta E/E_0) = 2(1-\cos\theta)$, where E_0 is the initial energy. This equation assumes that the total spin polarization is approximately constant during the rotation and that the dipolar energy can be neglected. Figure 2 shows the temperature and field dependence of $2(1-\cos\theta_c)$ for both superfluid phases. The slopes of the solid lines drawn through the data are exactly proportional to the inverse of the static field and seem to describe the ^{3}He-A data satisfactorily. However, in ^{3}He-B below 306 Oe, both the field and temperature dependence of $2(1-\cos\theta_c)$ cannot be accurately determined from these data. Almost no pressure dependence of θ_c was observed for either ^{3}He-A or ^{3}He-B as is demonstrated by the 306-Oe ^{3}He-B data. At constant H_0, the ratio of the slopes of the lines drawn through the ^{3}He-A and ^{3}He-B data is $(1-\cos\theta_c)_B/(1-\cos\theta_c)_A \approx 1.41$. Very close to T_c the transition from exponential to nonexponential behavior becomes less well defined and no data are displayed in this region. The data displayed in Fig. 2 can be used to qualitatively explain the results obtained by Corruccini and Osheroff, who in their work used only 90° rotations of the magnetization. At melting pressure for the fields employed in their work θ_c would be well above 90° in ^{3}He-B, and exponential relaxation should be and was observed. However in ^{3}He-A, θ_c would have been below 90° for fields above 460 Oe in the entire temperature range studied, and strictly nonexponential behavior should be and was observed.

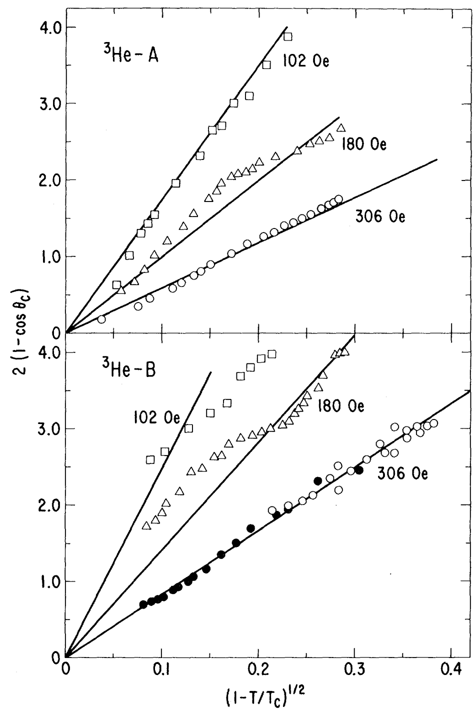

FIG. 2. Field and temperature dependence of the rotation angle, θ_c, for which the transition from exponential to nonexponential relaxation is observed. ^{3}He-A data were obtained at 26.1 bar. For ^{3}He-B, □□ and △△ are 21-bar data while ○○ and ●● are 23- and 16-bar data, respectively. The slopes of the lines drawn through the data are exactly inversely proportional to H_0.

Although the transition from exponential to nonexponential behavior occurs at a well-defined angle, θ_c, the transition from relaxations that are mainly linear in time to relaxations that are nearly proportional to the square root of time occurs gradually with increasing tip angle. Recently Vuorio[9] has suggested that magnetization supercurrents could explain the linear time dependence of the recovery of magnetization observed in ^{3}He-A. However, in view of this gradual change of the recovery process with increasing rotation angle, it is not at all clear that spin currents are responsible for the nonexponential relaxation results observed in this work.

Relaxations of the longitudinal magnetization that very nearly exhibited the theoretically predicted L-T time dependence were observed over a somewhat larger range of magnetic fields and temperatures than reported by Sager *et al.*[3] According to L-T, following a large-angle pulse the rate of dissipation of the excess energy in the spin system should be a constant in time. Experimentally, for those relaxations that have the L-T form following a 180° pulse, dE/dt can be defined[3,5] as $(-2\chi H_0^2/T_F)$, where T_F is the well-defined time for full recovery of the magnetization. A plot of dE/dt, obtained from the known susceptibility[7,8] and the measured H_0 and T_F, as a function of reduced temperature is shown in Fig. 3 for all the 180° pulse data obtained in ^{3}He-*A* and ^{3}He-*B* that very nearly exhibited the theoretical square-root time dependence. The theoretical curves displayed in Fig. 3 were derived from Ref. 5 using numerical quantities recently summarized by Wheatley.[10] In ^{3}He-*A* for 102 and 31 Oe, relaxations that nearly exhibited the theoretically predicted behavior were observed only near T_c. In 180 Oe, behavior much faster than the existing theory would predict was observed far away from T_c, but for $T/T_c > 0.97$ there was a clear tendency of these data toward a recovery process that was more linear in time. No L-T behavior was ever observed in 306 Oe. In ^{3}He-*B* for $H_0 = 180$ Oe, L-T behavior was observed over a wide range of temperatures. In 306 Oe, dE/dt was found to be faster than theoretically predicted while in 31 Oe no L-T relaxations were ever observed. In the temperature range where they can be compared, the ^{3}He-*B* 102- and 180-Oe data support the theoretical H^2 field dependence of dE/dt but do not establish it. According to L-T, the time for full recovery should be proportional to $1-\cos\theta$. However in this experiment a stronger angular dependence of the time for full recovery was observed in both superfluid phases.

The bulk of the nonexponential relaxation phenomena observed in this work was generally of the nature reported by Corruccini and Osheroff, where the magnetization recovered nearly linearly in time. An example of the extreme dependence on tip angle of the relaxation process in ^{3}He at 26 bar in 306 Oe is shown in Fig. 4. One of the most important results displayed by these

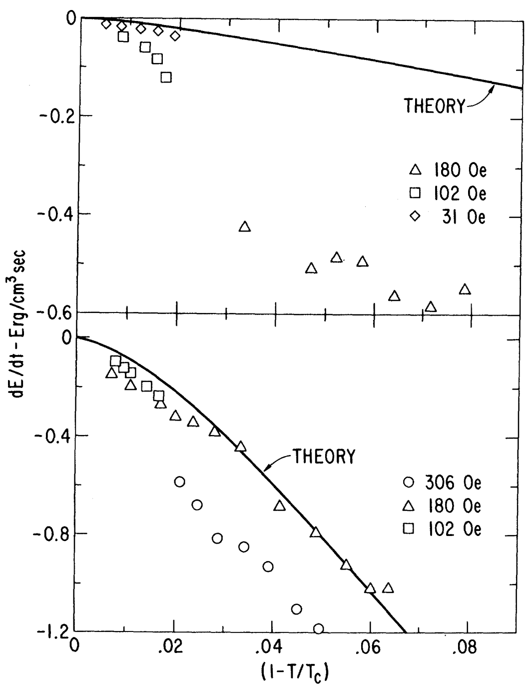

FIG. 3. The temperature dependence of the rate at which the excess energy in the spin system is dissipated, following a 180° spin tip, for those relaxations that very nearly have the theoretically predicted (L-T) time dependence. The upper portion displays data obtained in ^{3}He-*A* at 26.1 bar. The lower portion is for ^{3}He-*B* at 21 bar. The solid curves are the theoretically predicted temperature dependences.

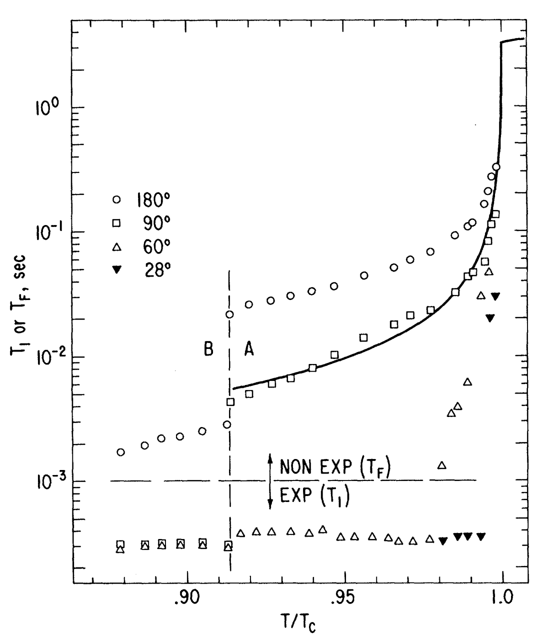

FIG. 4. The temperature dependence of the exponential relaxation time T_1 or the nonexponential time for full recovery T_F obtained at 26.1 bar in 306 Oe for four different spin-tipping angles. The solid curve drawn through the 90° pulse data is $T_F = [0.294 + 2083\,(1-T/T_c)]^{-1}$ sec.

data is that there is very little change in the exponential relaxation time, T_1, on going from ^{3}He-B to ^{3}He-A and that T_1 is nearly temperature independent in ^{3}He-A so long as the rotation angle is smaller than θ_c. For all the nearly exponential relaxations obtained in ^{3}He-A or ^{3}He-B, there was a slight tendency for T_1 to increase with increasing tip angle. Corruccini and Osheroff observed in ^{3}He-B that T_1 was independent of H_0 but was inversely proportional to the magnitude of the field gradient over the sample region. In this work, the inhomogeneity in H_0 over the sample region is linearly proportional to H_0 and was measured[6] to be $\Delta H = (0.016 \pm 0.005)H_0$. Assuming that there is no H_0 dependence of T_1 in ^{3}He-B, the data displayed in Fig. 4 agree with those of Ref. 2 once the difference in gradient field is accounted for. In ^{3}He-A, T_1 increased with decreasing field (or field gradient) but more slowly than in ^{3}He-B. For example, at $T/T_c = 0.96$ and at 26 bar, T_1 was found to be 0.34, 0.41, and 0.50 msec in magnetic fields of 306, 180, and 102 Oe, respectively.

The times for full recovery of the nonexponential relaxation data are also displayed in Fig. 4. No L-T behavior was observed at this field and pressure. The solid line drawn through the 90° pulse data demonstrates the approximate $(1 - T/T_c)^{-1}$ dependence of the relaxation time that was observed for almost all of those relaxations that had a nearly linear time dependence. The time for full recovery for those large-angle spin tips that produced a nearly linear recovery of the magnetization was found to be nearly inversely proportional to H_0, in agreement with the observations of Ref. 2. However, the time for full recovery decreased much faster with decreasing tip angle than the expected $1 - \cos\theta$ dependence. Very close to T_c there is nearly a factor of 10^3 difference between the relaxation time obtained for a 180° pulse and that obtained for a 28° pulse. At lower pressures and closer to T_c a similar field and temperature dependence was observed in ^{3}He-B for those relaxations which exhibited a nearly linear time dependence.

Although the magnetic field and field gradient dependences of these new relaxation results cannot be unambiguously separated, the work presented here strongly suggests that the mechanism for the relaxation of the longitudinal magnetization is similar for both superfluid phases of ^{3}He and extremely tip-angle dependent.

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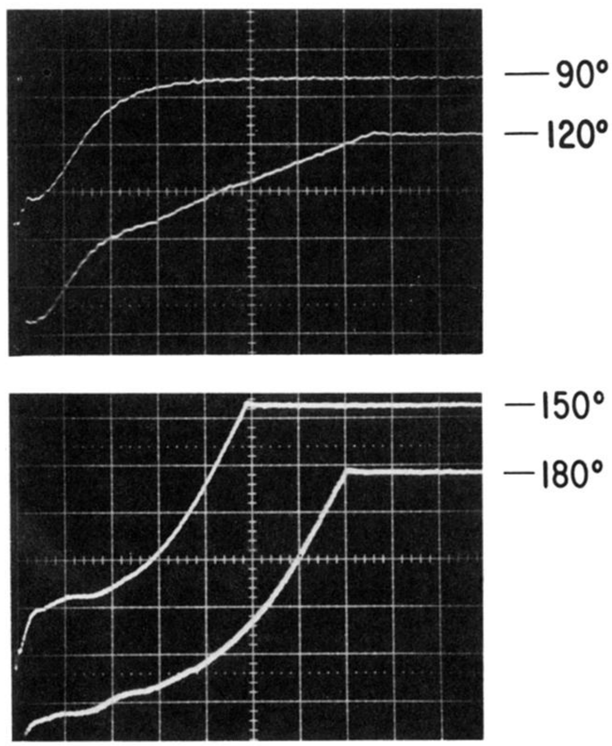

FIG. 1. Four examples of the relaxation of the longitudinal magnetization of superfluid ^{3}He-B, following 90°, 120°, 150°, and 180° rotations of the magnetization, obtained at $T/T_c = 0.967$ in 180 Oe at 21 bar. The time base for the 90° and 120° data was 0.5 msec/cm and for the 150° and 180° data was 2.0 msec/cm.