Magnetic Relaxation in Superfluid ^{3}He near the Critical Temperature

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Longitudinal magnetic relaxation in superfluid ^{3}He as described by the theory of Leggett and Takagi is observed for particular geometries within a very limited range of H_0 and $1-T/T_c$. Other observations demonstrate that, under certain conditions, the longitudinal magnetization in superfluid ^{3}He-A does not relax monotonically in time.

Superfluidity in ^{3}He has a dramatic effect on the relaxation of longitudinal magnetization as shown in the experiments of Ahonen, Haikala, and Krusius[1] and of Corruccini and Osheroff.[2] Using a SQUID-based technique, we have studied at temperatures close to T_c the relaxation of longitudinal magnetization following a spin-tipping pulse (usually 180°) in both A and B phases in several geometries and at various pressures and low magnetic fields. Related measurements have recently been mentioned by Webb.[3] Under suitable conditions of geometry, temperature, and field we have made the first observations of relaxation in which the square of the longitudinal magnetization difference recovers linearly in time, as predicted by Leggett and Takagi[4] (LT). Otherwise a variety of other relaxation phenomena are observed, including, for appropriate geometry, field, temperature, and pulse parameters, a nonmonotonic recovery of longitudinal magnetization in ^{3}He-A.

In our experiments, a static field $\vec{H}_0$ is trapped in a Nb cylinder. A saddle coil provides a transverse pulsed rf field of amplitude $2H_1$. Axial coils 6 mm long connected to a SQUID system[5] detect the component of magnetization along $\vec{H}_0$. We used three geometrical arrangements: (a) an "open" cylinder 4.0 mm in diameter with axis vertical and parallel to $\vec{H}_0$; (b) a "vertical-plate" geometry consisting of a stack of parallel plates 0.1 mm thick, spaced 0.22 mm apart, oriented with $\vec{H}_0$ parallel to the surfaces of the plates and $\vec{H}_1$ along their normal; (c) a "horizontal-plate" geometry consisting of a stack of plates of identical thickness and spacing to the above with a 1.2-mm-diam central hole and oriented with $\vec{H}_0$ along the normal to the plates. Magnetic temperatures were measured using cerium magnesium nitrate and converted to provisional absolute temperatures using the "La Jolla scale" of T_c versus pressure.[6] W used fields H_0 of 18, 30, 42, 60, and 84 G in the "open" cylinder; 18, 42, 60, and 84 G in the vertical plates; and 18, 42, and 60 G in the horizontal plates; $H_1 \lesssim 3$ G. For these parameters the development of a resonance frequency shift with increasing $1-T/T_c$ usually confined the measurements to small values of $1-T/T_c$.

Two extreme cases of longitudinal magnetic relaxation in ^{3}He-A following a 180° pulse are shown in Fig. 1. The circles give experimental data very nearly fitted by the solid line

$$M_z(t)=M_N[1-2(1-t/\tau_{\rm eff})^{1/2}], \quad (1)$$

where M_z is the component of magnetization parallel to $\vec{H}_0$, M_N is the normal-state magnetization, $t=0$ just after the pulse, and $\tau_{\rm eff}$ is the *well-defined* time at which the magnetization has fully recovered. We observed this simple yet striking behavior for the complete recovery only in the vertical plates and the open cylinder, only in 18 G, and only for $1-T/T_c$ in the range $0.0008 \lesssim 1-T/T_c \lesssim 0.005$. According to LT one has, fol-

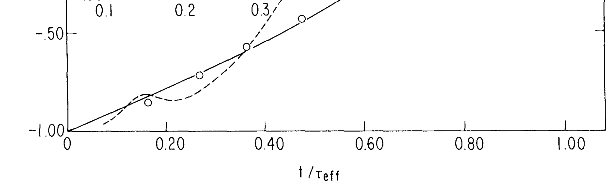

FIG. 1. Two examples of longitudinal relaxation in ^{3}He-A following a 180° tipping pulse in the vertical-plate geometry. The circles, fitted by Eq. (1) (solid line) were taken in 18 G at 21.6 bars and $1-T/T_c=0.0044$ with a $\tau_{\rm eff}$ of 23.9 msec. The dashed line, showing the magnetization reversal (expanded view in inset) is from data taken in 60 G at 29.2 bars and $1-T/T_c=0.0097$ with a $\tau_{\rm eff}$ of 38.6 msec.

lowing a 180° pulse,

$$\frac{dE}{dt} \equiv \frac{d}{dt}\left[\frac{(\chi H_0 - M_z)^2}{2\chi} + E_D\right]$$
$$= -\frac{1}{8}\gamma^{-2}\frac{\chi^2}{\chi_0}\frac{1-\lambda}{\lambda}\Omega_A{}^4\tau, \qquad (2)$$

where γ is the gyromagnetic ratio and, as $T \to T_c$, $\chi/\chi_0 = (1+\frac{1}{4}Z_0)^{-1}$, $\lambda = (\pi^2/16)(\Delta_0/kT_c)$, Ω_A is the measured parallel ringing angular frequency which varies as $(1-T/T_c)^{1/2}$ near T_c, and $\tau = \tau(0)$, the normal quasiparticle scattering time at the Fermi surface.[7] Hence as $T \to T_c$, the right-hand side varies as $(1-T/T_c)^{3/2}$. The dipolar energy, E_D, is negligible in these measurements. At a given T, integration of Eq. (2) gives a time dependence for M_z as in Eq. (1). A plot of $(\chi H_0 - M_z)^2$ is linear in time, and its slope may be used to find dE/dt. According to Eq. (2) we expect $(dE/dt)^{2/3}$ to be proportional to $1-T/T_c$ near T_c. Such a plot for the vertical plates is shown in Fig. 2, confirming further the theoretical calculations of LT. Using[8] $Z_0 = -3.05$, $\Delta C/C_N = 1.55$, $\tau(0)T_c{}^2 = 0.35$ μsec mK^2, $T_c = 2.406$ mK, and $\Omega_A{}^2 = (1.55\times 10^{12}\ \text{sec}^{-2})(1-T/T_c)$, we find the theoretical line shown. The comparison is only fair, which may relate to inaccuracy in the numerical data.

An increase of field to 30 G in the open cylinder and to 42 G in the vertical plates led to more complex relaxation, so comparison with the LT predictions is less relevant, and in the horizontal plates LT behavior was never observed. Frequently the magnetization showed a linear variation with time, but only over part of the recovery.

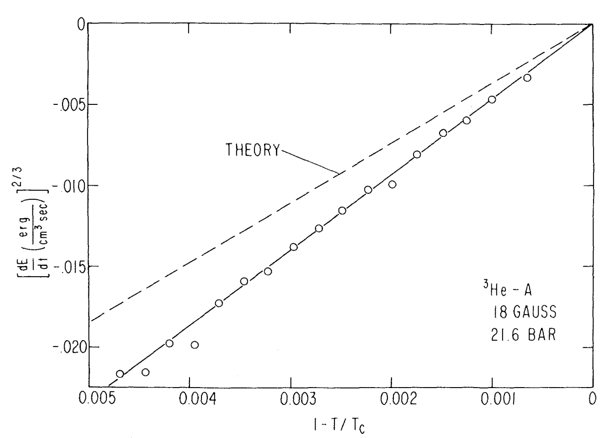

FIG. 2. Temperature dependence of the energy relaxation rate following a 180° tipping pulse: Leggett-Takagi theory, dashed line; linear fit to experimental data, solid line.

In the open geometry, an increase in the static field gave rise to a marked increase in the percentage of magnetism recovering linearly. By 84 G there is a clear tendency toward behavior like that observed by Corruccini and Osheroff[2] and explained by Vuorio[9] in terms of spin currents characterized by a time-independent velocity profile. Although the details of the recovery differ from one field to the next the overall time for recovery, τ_{eff}, is proportional to H_0 (with the exception of the 18-G points which relax faster than the proportionality would dictate); the Leggett-Takagi theory would predict an $H_0{}^2$ dependence of this property.

The profound effect of geometry and an extreme non-LT relaxation are epitomized by the remarkable behavior that we observed in the open cylinder in 42 G and in the vertical plates in 60 G where, under certain conditions, $M_z(t)$ does not relax monotonically in time. One such example, for a pressure of 29.2 bars and at $1-T/T_c = 0.01$, is the dashed line in Fig. 1 which shows the SQUID detector output normalized by the equilibrium magnetization of the normal Fermi liquid plotted against time normalized by τ_{eff}, the time for complete recovery. The inset is an expanded view of the temporary reversal in the relaxation. [Note also the "tail" in which $M_z(t)$ is approximately linear in time.] The reversal of the relaxation in 60 G in the vertical plates is characterized in Fig. 3. Figure 3(a) gives τ_{eff} as a function of $1-T/T_c$ and provides the normalizing factor for Figs. 3(c) and 3(e). The circles on 3(b) and 3(c) refer to the normalized coordinates of the inflection point of the reversal and the triangles to those of a second feature, not present in Fig. 1 but seen at other temperatures, where the rate of recovery slowed but did not reverse. Figures 3(d) and 3(e) give, respectively, the total magnitude of the magnetization reversal $(M_z{}^{\max} - M_z{}^{\min})$, normalized by $\chi_N H_0$, and the time $(t_{\min} - t_{\max})$ between the local maximum and minimum of the reversal, normalized by τ_{eff}, as a function of $1-T/T_c$. We note that the size of the magnetization reversal is compatible with the measured[10] susceptibility anisotropy (as if the reversal corresponded to the superfluid spins turning away from $\vec{H}_0$) and that the time interval $t_{\min} - t_{\max}$ is of the same order as the orbital relaxation time.[10] Additionally, we observed the following: (a) In the open cylinder in 42 G with a 24-cycle 180° pulse, the reversal could be destroyed by changing the rf pulse frequency away from the Larmor frequency (136 kHz) by ± 50 Hz. (b) In the verti-

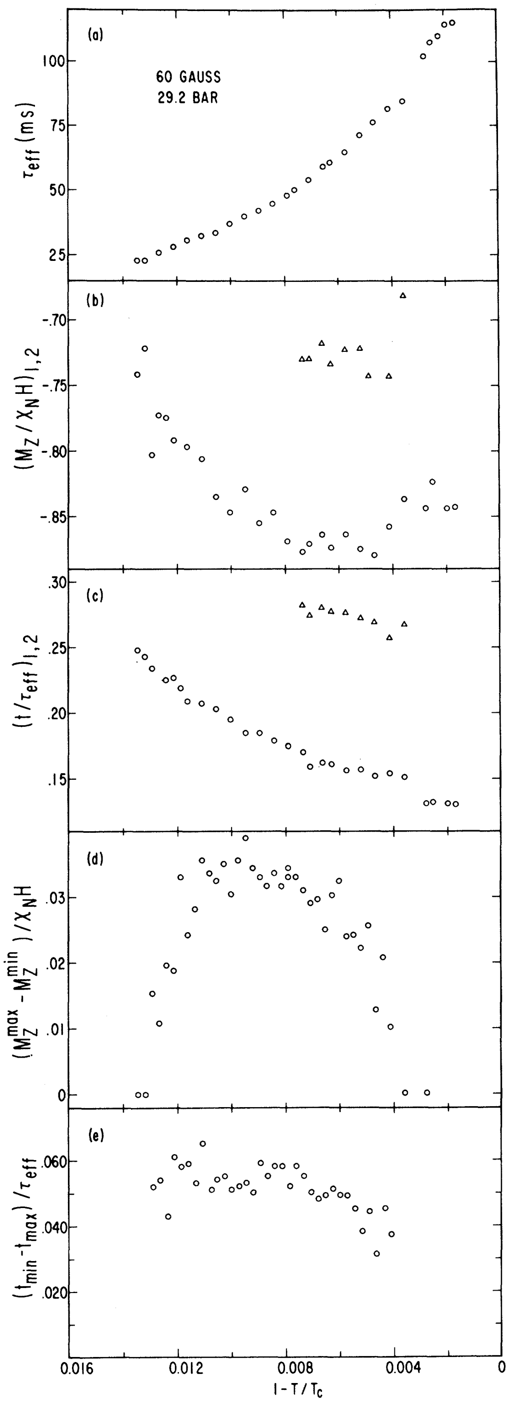

FIG. 3. Characterization of magnetization reversal observed in ^{3}He-A: (a), τ_{eff} vs $1-T/T_c$ to provide a normalization factor for (c) and (e); (b) and (b), normalized values for M_z and t at which the inflection points of the features occur. Triangles represent a second feature in which the relaxation rate did not actually reverse; (d) and (e), normalized magnitude and duration of the reversal.

cal plates in 60 G with a 21-cycle 180° pulse, the maximum reversal occurred with an rf pulse frequency 400 Hz below the Larmor frequency (194 kHz), while the reversal was decreased for 180° pulses of 42 and 10 cycles. (c) The reversal was observed in the open cylinder only in 42 G with a maximum value of $(M_z^{max} - M_z^{min})/\chi_N H_0 \simeq 0.007$. In the vertical plates the reversal occurred only in 60 G with a maximum magnitude of $(M_z^{max} - M_z^{min})/\chi_N H_0 \simeq 0.035$ [Fig. 3(d)]. In the horizontal plates, no feature was ever observed.

In ^{3}He-B at 19.6 bars we found a time dependence of $M_z(t)$ as in Eq. (1) for only the open cylinder, for $1-T/T_c \lesssim 0.005$, and for a field of 30 G. The corresponding dE/dt depended on temperature approximately as $1-T/T_c$, rather than $(1-T/T_c)^{3/2}$. In other fields and geometries, the relaxation was more complex. In all fields and geometries, following a *nominal* 180° pulse, the relaxation time in ^{3}He-B drops precipitously at T_c to a τ_{eff} of $\lesssim 5$ msec at $1-T/T_c \simeq 0.005$. For $1-T/T_c \gtrsim 0.005$ the character of the relaxation following a nominal 180° pulse changes completely, with the time for total relaxation increasing to 20 to 30 msec. Experiments in the horizontal plates suggest that this phenomenon may result from an actual tipping angle of close to 100° when a nominal 180° pulse is used, suggestive of a frequency shift for tipping angles $\gtrsim 104°$ as proposed by Brinkman and Smith.[11] When we use a 108° pulse the relaxation time drops to about 20 msec on cooling in the range $0.002 > 1-T/T_c > 0$ and then increases gradually to ~ 30 msec for $1-T/T_c \sim 0.05$. These times are not inconsistent with the zero-gradient results of Ref. 2 for the B phase. At no time is LT-like behavior observed in ^{3}He-B following a 108° pulse.

The geometry effects we observed can be summarized as follows: (a) Relaxation in the open and vertical-plate geometries was very similar in ^{3}He-A except for the changes in the reversal described above. (b) In the horizontal plates in ^{3}He-A the relaxation was much slower and neither the LT time dependence nor the reversal were observed. (c) In ^{3}He-B the LT time dependence was found only in the open geometry although the relaxation following a nominal 180° pulse near T_c had a well-defined τ_{eff} in all geometries and then changed to an exponential form at larger $1-T/T_c$. (d) Experiments done only in the horizontal plates indicate a significant difference in the relaxation in ^{3}He-B following nominal 108° and 180° pulses for $1-T/T_c \lesssim 0.01$. A more complete description of these experiments will be presented elsewhere.

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Plasticity in a Smectic-*A* Liquid Crystal

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We present direct measurements of the layer rigidity in a smectic-A liquid crystal, 4′-n-octyloxy-4-cyanobiphenyl. For low strain normal to the layers, the instantaneous induced stress is elastic and gives $B = 0.8 \times 10^7$ cgs units at 60°C. In response to a steplike strain, the stress relaxes almost completely, with a time constant ~ 50 ms. The relaxation stops for a residual strain smaller than $\frac{1}{2}$ layer over the total thickness of the smectic sample.

Smectic-A liquid crystals are liquid layered systems, with molecules normal to the layers.[1] To describe their mechanical properties, de Gennes[2] has developed a model which predicts a solidlike reaction to strains normal to the layers. Experimental verifications[3-8] of this model have been made through the threshold observation of two kinds of mechanical instabilities: a critical-layer dilation for a layer undulation instability, or a critical compression for a molecular tilt instability inside the layers. From the dynamics of the observed texture distortion, a relaxation of stresses was guessed.[3,4,7,8] Up to now all the smecticlike elastic-modulus determinations are made by comparison with a nematic elastic constant and are therefore indirect. There are not any observations of stress relaxation either. In this Letter we give the first direct measurement of the isothermal layer compressibility modulus, observing also for the first time a fast and quasi total relaxation of stresses normal to the layers.

Let us consider a single crystal of smectic A, in the homeotropic geometry, where layers are parallel to the boundary glass plates (Fig. 1). We apply a quasi-instantaneous dilation normal to the layers, produced by a piezoelectric ceramic A driven by a steplike voltage V_A. We measure the pressure transmitted through the liquid crystal as a function of time by measuring the voltage across another piezoelectric ceramic M. Using classical[9] notations we can write the free dilation produced by the ceramic A as $d_{33}V_A$; let us call d_i and Y_i the thickness and the Young modulus of the materials which transmit the

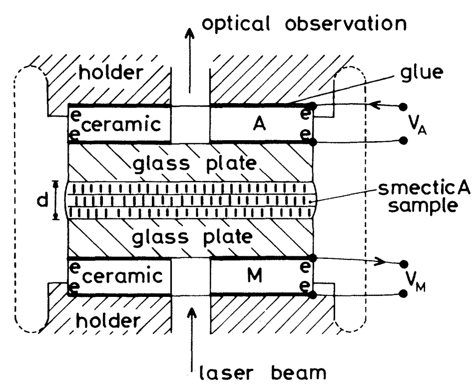

FIG. 1. Sample disposition. e, semitransparent electrodes.