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Relaxation of the Wall-Pinned Magnetization Ringing Mode in Superfluid ^{3}He-B*

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Observations of the wall-pinned mode in ^{3}He-B allow new magnetic relaxation phenomena to be studied. Excepting the quantitative value of the zero-time ringing frequency, comparison of experiment with theory is satisfactory, including a linear dependence of the square of the ringing period on time and a square-root singularity near T_c in the relaxation parameter.

Relaxation of the remarkable dynamical spin phenomena which can be observed in superfluid ^{3}He has been the subject of much recent experimental[1,2] and theoretical[3-8] work. The relaxation takes a particularly interesting form in the case of the wall-pinned magnetization ringing mode[9] in ^{3}He-B. The undamped mode has been studied in detail theoretically by Maki and Hu[10] and by Brinkman.[11] This ringing mode occurs in ^{3}He-B when a magnetic field ΔH parallel to the wall of a ^{3}He container is turned off, leaving zero field. If ΔH is small enough the rotation axis[12] is initially oriented perpendicular to the wall by very weak forces, but when the field is turned off much larger dipolar forces come into play and there results[11] a mutual precession of magnetization and rotation axes about one another *even in zero external field.* The resultant magnetizational ringing relaxes[9] by a *decrease of frequency with time* without the substantial decrease of amplitude with time which we have observed in other ringing phenomena in ^{3}He-B. Following a suggestion from Professor Maki, we found that our 1974 relaxation data[9] could be fitted by the formula

$$f_R(t)^{-2} = f_R(0)^{-2} + \alpha t, \qquad (1)$$

where f_R is the ringing frequency at time t and α is a parameter. Since the time dependence in (1) has been confirmed quantitatively in our present measurements, the simple conditions imposed on the ^{3}He (zero final field) lead us to expect that the intrinsic relaxation mechanism currently being discussed theoretically will be the principal mechanism for relaxation of the wall-pinned mode, thus making it an appropriate means for testing the new theoretical relaxational concepts.

According to Leggett and Takagi,[4] magnetization is transferred from one interpenetrating magnetic superfluid to another via the coherent torque on the Cooper pairs, thereby putting superfluid and excitations out of equilibrium in a given spin band. Relaxation of superfluid and normal fluid toward equilibrium then ensues via collisions at constant spin within a band. Analysis of the wall-pinned mode by Leggett[13] and by Maki and Ebisawa[7] leads to the result

$$\alpha = \tfrac{3}{4}(2\pi)^2[1+\tfrac{1}{4}Z_0(\tfrac{2}{3}+\tfrac{1}{3}Y)]^{-1}(\lambda^{-1}-1)\tau, \qquad (2)$$

where Z_0 is the average Landau spin parameter,[12] Y is the Yosida function,[12] τ is an empirical collision time, and $\lambda = 2(1-f)/(2+Y)$ where

$$f = \int_0^\infty \tfrac{1}{2}\beta\, d\epsilon[\epsilon^2/(\epsilon^2+\Delta^2)]\,\mathrm{sech}^2\tfrac{1}{2}\beta(\epsilon^2+\Delta^2)^{1/2}$$

and Δ is the assumed isotropic energy gap.[4] Near the critical temperature T_c the damping parameter α is approximated by[13]

$$\alpha \simeq 18(3/2)^{1/2}(\Delta C/C_N)^{-1/2} \times(1+\tfrac{1}{4}Z_0)^{-1}\tau(1-T/T_c)^{-1/2}, \qquad (3)$$

where $\Delta C/C_N$ is the ratio of the specific heat jump to the normal specific heat at T_c. In the above it is assumed that ^{3}He-B reflects the Balian-Werthamer (BW) state[12] for which[10,11]

$$f_R(0)^2 = [2(1-\cos\theta)]^{-1}(\gamma\Delta H/2\pi)^2, \qquad (4)$$

where γ is the gyromagnetic ratio and θ, for small enough ΔH, is the angle of rotation of spin with respect to space coordinates which minimizes the dipolar energy ($\cos\theta = -\frac{1}{4}$ is expected for the BW state[12]). Thus, the theory predicts that the square of the ringing period increases linearly with time with an intercept which is independent of temperature and pressure but proportional to $(\Delta H)^{-2}$ and with a slope which increases with increasing temperature leading to a square-root singularity near T_c.

The measurements were made on ^{3}He confined to a rectangular cavity several centimeters long with cross section 1 mm$\times$10 mm, $\Delta\vec{H}$ being perpendicular to this section. The field ΔH was produced by a long close-wound solenoid of niobium wire. The ringing signal was picked up by one of

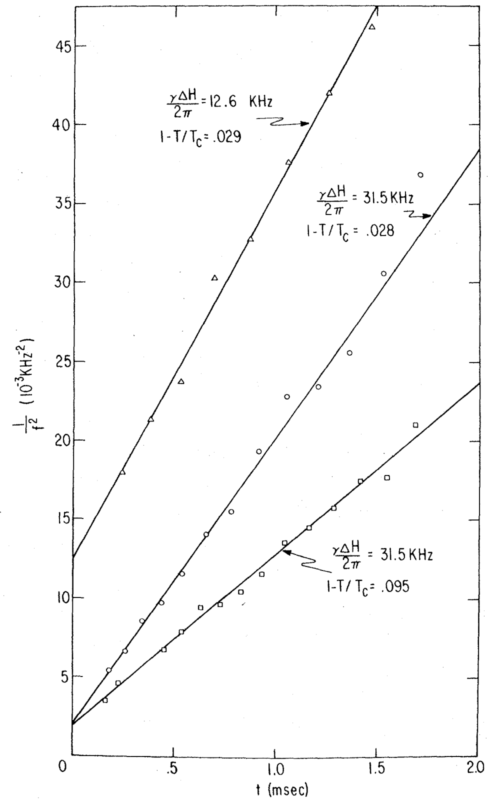

FIG. 1. Nature of the relaxation of the wall-pinned mode in ^{3}He-B at 20.7 bar. The values of $1-T/T_c$, $\gamma\Delta H/2\pi$ kHz, and $\Omega_\parallel/2\pi$ kHz are respectively, 0.029, 12.6 and 50 (triangles) 0.028, 31.5, 51 (circles); and 0.095, 31.5, and 92 (squares).

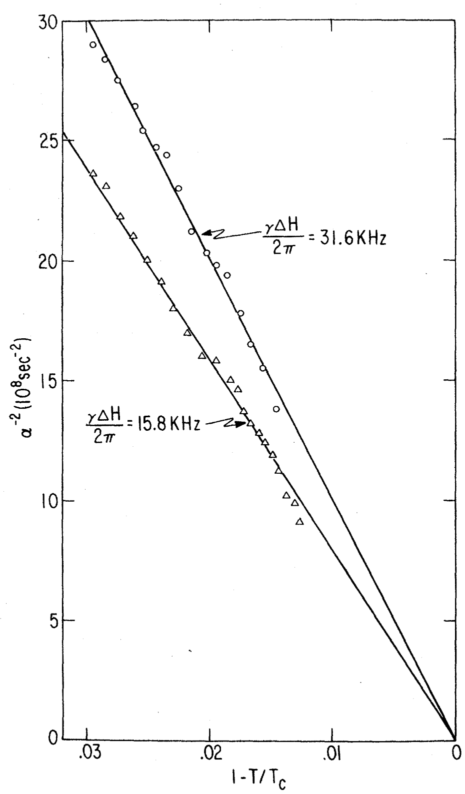

FIG. 2. Evidence for the square-root singularity in the relaxation parameter α at 20.7 bar for $\gamma\Delta H/2\pi$ =15.8 kHz (triangles) and for 31.6 kHz (circles).

a pair of astatically wound niobium coils which were connected to a 160-MHz rf-biased SQUID. The ^{3}He and coil systems were surrounded by a niobium magnetic shield in which the trapped field was less than 0.1 G. The ratio of ΔH to current change was measured in a separate experiment using a bismuth probe. Temperature was sensed by a small cesium magnesium nitrate (CMN) powder thermometer located elsewhere in the cell but with as tight thermal coupling as possible. Cooling was achieved by means of powdered CMN. The ^{3}He temperature could be stabilized for long periods of time by slowly changing the residual field on the CMN refrigerant.

Experimental data at 20.7 bar illustrating the relaxation phenomenon for two values of ΔH and for two temperatures at fixed ΔH are shown in Fig. 1. These are derived from observations of the ringing on an oscilloscope using a calibrated time delay and visual signal averaging. The quantity $f_R(0)/(\gamma\Delta H/2\pi)$ is found to be constant at 0.688 ± 0.016 over the measured pressure range from 13.5 to 20.7 bar and over a maximum range of $1-T/T_c$ from 0.03 to 0.12. According to Eq. (4) this corresponds to $\cos\theta = -0.05 \pm 0.05$ as opposed to the value $-\frac{1}{4}$ predicted by theory[12] and deduced[14] from spin-tipping measurements[15] at melting pressure using the same equations[11] as were used to obtain (4). Alternatively one could say that $\cos\theta = -\frac{1}{4}$ but that the *effective* field turned off is 1.09 ± 0.03 times the external field turned off. In spite of this significant discrepancy we shall continue to use the BW-state expressions (2) and (3) to interpret our measurements.

The dependence of α^{-2} on temperature near T_c is shown in Fig. 2, which also shows qualitatively an effect of ΔH on α. This plot should be linear if the predicted square-root singularity, Eq. (3), exists. Observations for a given ΔH could not be carried closer to T_c than shown, since for somewhat smaller $1-T/T_c$ "normal" B-phase ringing appeared, corresponding probably to a change of

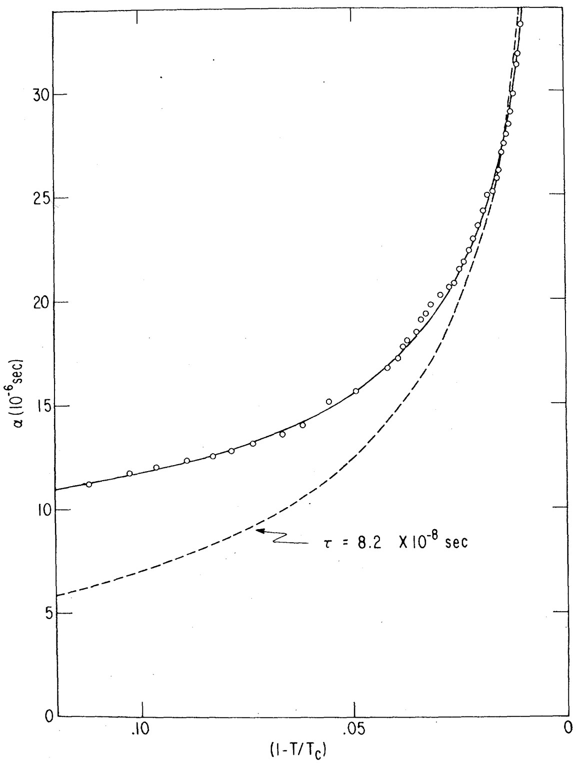

FIG. 3. Dependence of the relaxation parameter α on reduced temperature difference at 20.7 bar for $\gamma\Delta H/2\pi = 15.8$ kHz. The dashed curve is a fit to theory with a constant τ of 8.2×10^{-8} sec. The smooth curve is a fit with a temperature-dependent τ (see text).

texture. A plot of the square of this normal ringing frequency versus T leads to the same T_c as found by plotting α^{-2} versus T, increasing our confidence in the existence of the square-root singularity in α.

The variation of α with $1-T/T_c$ at 20.7 bar and a fixed ΔH is shown over a more extended range on Fig. 3. The decrease of α with increasing ΔH is not as rapid as $(\Delta H)^2$. If we fit Eq. (2) to the data shown near T_c by adjusting τ we get the dashed curve shown on Fig. 3 with $\tau = 8.2\times10^{-8}$ sec. Experiment and theory fit reasonably well over the whole temperature range if one takes

$$\tau = \tau_H[1 + 6.2(1 - T/T_c) + 20.5(1 - T/T_c)^2]$$

with $\tau_H = 7.5\times10^{-8}$ sec. A crude extrapolation of τ_H to zero ΔH gives $\tau_0 = 6.2\times10^{-8}$ sec. This value is intermediate between the experimentally deduced[12] relaxation times for viscosity and thermal conductivity. That the Leggett-Takagi τ approaches a value characteristic of the normal state has recently been suggested by Bhattacharyya, Pethick, and Smith.[16]

We also studied the wall-pinned mode and its relaxation as a fundtion of $H_0/\Delta H$, whére H_0 is the steady field *after* the field ΔH is turned off. ($H_0 = 0$ for Figs. 1–3.) These results will be presented elsewhere, but we comment that the reason Webb, Kleinberg, and Wheatley[9] and Leggett and Wheatley[12] were unable to observe a wall-pinned mode for values of H_0 of 5 G or more lies in the large *damping* of the mode and probably not in an unusually high frequency or in a change of texture.

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