Polarization rates of solid ^{3}He formed by rapid compressions

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The time dependence of the magnetization of solid ^{3}He formed in a Pomeranchuk cell at high fields ($B = 2.45$ and 3.34 T) and low temperatures ($T < 10$ mK) in pulsed compressions is studied. A relaxation rate faster than that for either the liquid or solid is observed. Below the A_2 superfluid transition, a still faster rate is seen provided that the rate of growth of solid is less than a critical value.

There has been a considerable interest in the way that solid ^{3}He grows from the liquid in a Pomeranchuk cell, especially as to whether or not in a large magnetic field the solid forms with equilibrium magnetization.[1] Schuberth, Bakalyar, and Adams,[2] discovered a sudden decrease in the pressure below the superfluid A_2 transition, which they called the "backstep," and initially interpreted as a phase transition. Yu and Anderson,[3] however, suggested that the backstep could be associated with the growth of underpolarized solid and its subsequent return to equilibrium following the A_2 transition. Additional measurements by Schuberth *et al.*,[4] Yurke *et al.*,[5] and Godfrin *et al.*[6] have all supported the Yu-Anderson model.

We present measurements of the growth of polarization of solid produced by transient techniques. We apply a step pulse of ^{4}He pressure and monitor the ^{3}He pressure and magnetization. In this way we produce some new solid very quickly and measure how fast the magnetization acquires its equilibrium value. Below the A_2 transition two distinct types of behavior are found — a slow and a fast response depending on the rate of growth of solid and the temperature. The fast response corresponds to the growth of polarized solid and the slow response to the growth of unpolarized solid and its subsequent polarization. The backstep occurs during the slow response.

The experiments were done using a bellows-type Pomeranchuk cell equipped with capacitive pressure transducers for measuring the ^{3}He and ^{4}He pressures, P_3 and P_4. Changes in volume, ΔV, can be obtained from changes in the pressure and the measured spring constant of the bellows and are given by

$$-3.0\Delta V = 3.0\Delta P_4 - \Delta P_3 \quad (1)$$

with pressures in MPa and ΔV in cm^3. The amount of solid grown, Δn_s, may be determined from

$$\Delta V = (v_s - v_l)\Delta n_s - (n_s K_s v_s + n_l K_l v_l)\Delta P_3 \ , \quad (2)$$

where v is the molar volume, n is the number of moles, and K is the compressibility of the solid s and liquid l. A sample with ^{4}He impurity of 1000 ppm was used to provide a ^{4}He layer on the cell walls. The magnetization was observed by NMR with a frequency-modulation Rollin-type spectrometer. A lock-in amplifier operating at twice the modulation frequency sampled the integral of the absorption.

Typical data for two compressional pulses below T_{A_2} and in a 3.34-T field are shown in Fig. 1. The chart traces the applied ^{4}He pressure step and the responses of the ^{3}He pressure P_3 and magnetization M. The first pulse [Fig. 1(a)] is representative of the fast behavior in which there is a rapid response of P_3 and a rapid growth of M. The second pulse [Fig.

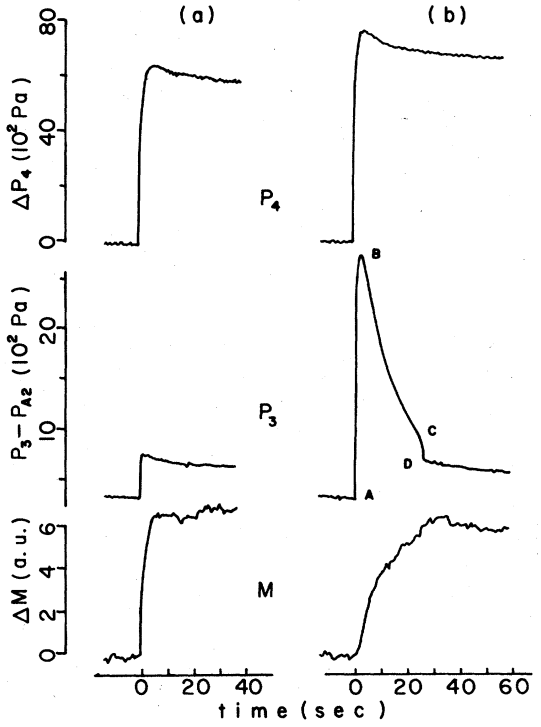

FIG. 1. ^{4}He and ^{3}He pressures and magnetization (in arbitrary units) as a function of time for the fast response (a) and the slow response (b), in a field of 3.34 T and at a temperature of about 2.3 mK.

1(b)] shows the dramatically different behavior in which M responds much slower with a backstep occurring in the pressure near the end of the recovery. The difference between the slow and fast responses is caused by the larger ^{4}He step for the slow response. By applying the same size step with different rise times, we can induce both types of behavior, indicating that the difference is caused by the rate of growth. The final pressure for both the fast and slow cases is nearly the same. For $T > T_{A_2}$, the response of the system is identical to that in the slow response for $T < T_{A_2}$, except that the backstep is absent.

Figure 1(a) shows the last of a sequence of successively larger pulses at 2.3 mK, before the slow behavior occurred. The magnetization rise time is less than one sec, the shortest time resolved by the electronics. The rapid increase in magnetization indicates that the solid is formed polarized. Therefore, this case represents the maximum rate for growing polarized solid at this temperature. We show later that the slow behavior is characteristic of the initial growth of underpolarized solid. From Eqs. (1) and (2), we find for the pulse in Fig. 1(a), $\Delta V_s = 0.11$ cm^3. The ^{3}He and ^{4}He pressure rise times are both 0.5 sec and are probably determined by the ^{4}He capillary. Using 0.5 sec as the time for the solid to form, we obtain $\dot{V}_{s,\max} = 0.2$ cm^3/sec for the maximum growth rate at 2.3 mK. The temperature dependence of this rate for two applied magnetic fields is shown in Fig. 2. No field dependence is observed.

Using the assumption of Yu and Anderson[3] that the magnetization is supplied from the liquid, we give an argument to show why there should be a maximum growth rate for polarized solid. In the model, the magnetization of the superfluid not only relaxes locally, but also flows to bring as much magnetization to the solid interface as possible. Assume that the new solid grows on the previously grown solid in the form of a thin layer of area A. In order for a volume of solid, V_s, to form with the proper magnetization, the magnetic moment must be supplied at a rate $M_s \dot{V}_s$ from the adjacent layer of superfluid. The thickness of this layer is the product of the supercurrent critical velocity v_c and the magnetization rise time Δt. This layer of liquid can produce the magnetic moment, through relaxation, at a rate $A v_c \Delta t M_l / T_{1l}$ where T_{1l} is the relaxation time of the liquid. Equating the two rates relates the maximum growth rate to the rise time,

$$\dot{V}_{s,\max} = (A v_c M_l / M_s T_{1l}) \Delta t \quad . \tag{3}$$

For the data of Fig. 1, we estimate the solid polarization to be 70% and $A = 10$ cm^2, to within a factor of 2. Using a liquid polarization of 1.5%,[7] $v_c = 0.05$ cm/sec,[3] and $T_{1l} = 6$ msec,[8] we obtain $\dot{V}_{s,\max} = 1$ cm^3/sec. That we have overestimated the effect is expected because we have ignored the details of the superfluid flow and relaxation. Also, neither T_{1l} nor v_s has been measured in fields as large as we used. The increase in $\dot{V}_{s,\max}$ with decreasing temperature occurs because of the large decrease in T_{1l} below T_{A_2}.[8]

As shown in Fig. 1(b), the slow behavior is characterized by an initial jump in pressure and a slow relaxation back to the new equilibrium value. From changes in the pressures, we find that during the initiating step, AB, almost the same quantity of solid was formed as in the fast case. The magnetization initially does not change, indicating that this solid is underpolarized. It then increases at a rate approximately equal to that of the pressure decrease. During the recovery the volume of the cell remained constant within experimental error and about 10% more solid formed. At temperatures below T_{A_2} the backstep occurs always when the magnetization almost reaches its equilibrium value. Coincident with the backstep was a slight increase in magnetization. This is expected because of the additional solid formed there.[4] After the backstep both the magnetization and pressure have reached their equilibrium values and then follow the warming of the cell.

Time constants for both the pressure and magnetization recovery are substantially shorter than would be expected by a mechanism whereby the liquid relaxes at a wall of the sample chamber and transports magnetization via diffusion to the interface. It would be likely that all the walls are covered with solid, and, furthermore, the ^{4}He impurity should reduce wall relaxation. The magnitude of the time constant can be explained by a fast relaxation mechanism acting at

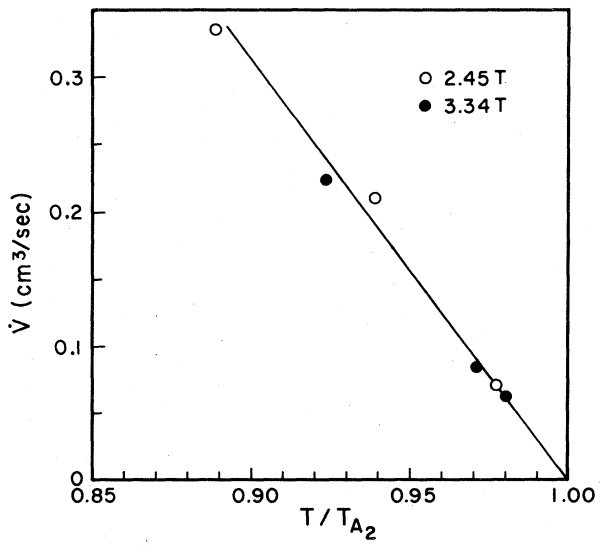

FIG. 2. Maximum growth rate for the fast response as a function of reduced temperature. The line is drawn to guide the eye.

the interface combined with the diffusion of spin energy to the interface where it is dissipated in the liquid. Such a relaxation would not be surprising if there is a rapid exchange of atoms between the solid and liquid. We can estimate the time constant by assuming that the solid grew in the form of a cylindrical shell of thickness Δx. The time constant τ associated with the diffusion of magnetization into the shell is $\langle(\Delta x)^2\rangle/2D$ where D is the diffusion coefficient of spin energy, both Zeeman and exchange. From the magnetization change we estimate $\Delta x = 4 \times 10^{-3}$ cm for the data in Fig. 1, and using $D = 2 \times 10^{-7}$ cm^2/sec,[9] we find $\tau = 40$ sec. The measured time constant is 10 sec for this case. Determination of the variation of τ with the thickness of the layer ($\sim \Delta P_4$) was not generally possible, particularly near T_{A_2}, because of the interruption of the curve by the backstep. The time between the pulse and the backstep varied roughly linearly with ΔP_4. The order of magnitude agreement gives support for an interfacial relaxation mechanism which provides close thermal contact between the liquid and solid.

We suggest the following detailed mechanism for the backstep, based on our observations. Consider the case where the unpolarized solid is formed below T_{A_2}. The spin temperature of the newly formed solid, both Zeeman and exchange, is infinite. The solid heats up the adjacent layer of liquid, by means of the interfacial relaxation mechanism, to a point above the A transitions corresponding to the observed pressure on the zero-magnetization melting curve. This is shown as the path $A'B'$ in Fig. 3 for the data in Fig. 1. The melting curves shown here are interpolated and extrapolated from previous work.[2,10] During the recovery the pressure is assumed to be determined by the interface of the magnetizing solid and the adjacent liquid in close thermal contact with it. Thus some path $B'D'$, not necessarily a straight line, will be followed with the backstep occurring when the superfluid transition, point C', is reached. Then the fast response mechanism quickly brings the system to equilibrium. The pressures of the backstep are shown as the horizontal lines for the data of Fig. 1 and for other data taken at 2.45 T. These lines nearly intersect the recovery lines at the superfluid A_2 transition, indicating qualitative agreement for the pressure at which the backstep occurs (point C in Fig. 1).

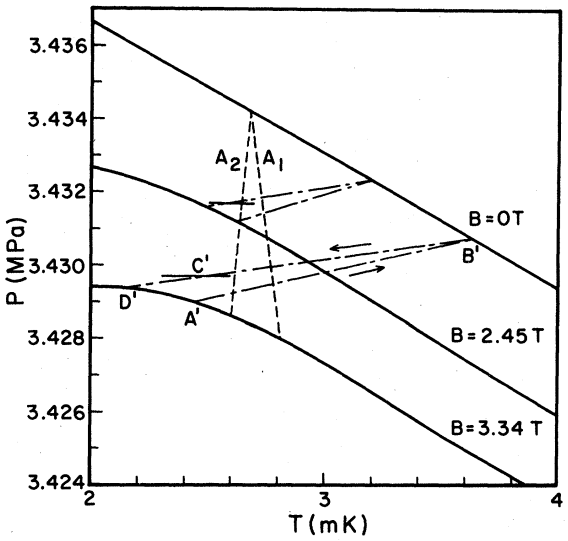

FIG. 3. Conjectured paths taken by the newly formed solid on melting curves appropriate to the fields used. The superfluid A_1 and A_2 transitions are shown by dashed lines. The horizontal lines are the observed pressures where the backstep occurs. The points A',B',C',D' correspond to the points A,B,C,D in Fig. 1.

In the normal fluid, for both large and small pulses, the behavior was identical to that in the slow response of Fig. 1(b), except that the backstep feature at C was absent. Thus the slow portion of the recovery for $T < T_{A_2}$ appears to be identical to that in the normal fluid. This provides additional support for the model used above (see Fig. 3) to explain the slow response, in which the backstep is just the A_2 transition occurring at liquid-solid interface.

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