A POSSIBLE EXPLANATION FOR THE RECENTLY OBSERVED PHASE TRANSITION IN SOLID ^{3}He IN HIGH MAGNETIC FIELDS

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Received 18 July 1979

The phase transition-like phenomenon recently observed in solid ^{3}He in high magnetic fields may be related to the change in the spin relaxation mechanisms of liquid ^{3}He in the region of the A superfluid transition.

Schuberth, Bakalyar and Adams (SBA) [1] have recently reported evidence for a phase transition on the ^{3}He melting curve near the A_1-A_2 superfluid transitions in high magnetic fields. The phenomenon was manifested as a backstep in the chart traces of pressure versus time. There were, however, several odd characteristics. For example, although the feature has only been seen in high magnetic fields (~20 kG), it occurs at the same temperature for different fields. In addition, it was not observed when the sample was warmed. Latent heat measurements indicated that there was a significant drop in the entropy (~$0.1R\ln 2$). It should be kept in mind that the magnetic properties of liquid ^{3}He change dramatically as the temperature decreases below the A superfluid transition temperature T_c. Corruccini and Osheroff [2] have found that the longitudinal spin relaxation time T_1 drops by three orders of magnitude below T_c. Anderson [3] and Vuorio [4] have suggested that this drop can be explained by magnetic supercurrents of spin-up and spin-down superfluids. We propose the following explanation of the phenomenon seen by SBA. Above the superfluid transition, the solid that is formed by compression may not have equilibrium magnetization because spin relaxation and spin diffusion processes are too slow to provide the necessary magnetization to the normal liquid from which the solid is formed. This magnetization deficit increases with the rate of compression. Below T_c, however, the drop in T_1 and the onset of supercurrents may imply that magnetization can be supplied rapidly enough to allow solid to form with equilibrium polarization. Using the following expression for the entropy of the solid [5]:

$$\frac{\Delta S}{Nk}=\frac{S(T,H)-S(T,0)}{Nk}=-\frac{1}{2}\left(\frac{\mu H}{k(T-\theta)}\right)^2 ,$$

where θ is the Néel temperature, we estimate $\Delta S/Nk$ ~$0.1 \ln 2$ in agreement with latent heat measurements. This is a larger drop in entropy than that associated with the pressure versus time chart traces because of solid formation is much faster in the latent heat measurements.

We can also compare the rate of change of the magnetization of the solid and the liquid above and below T_c. The change in T_1 at the superfluid transition indicates that the spin relaxation mechanism has changed. A more specific model involves the onset of supercurrents which are much more effective in transporting magnetization than is spin diffusion. We now present two calculations—one with T_1 and one with spin diffusion and supercurrents causing the change in the magnetization deficit.

In order to form solid with equilibrium magnetization, the rate at which the magnetization must be supplied to the solid can be expressed as

$$\dot{M}_s \equiv (\mathrm{d}M/\mathrm{d}t)_{\mathrm{solid}} \approx (\mathrm{d}y_s/\mathrm{d}t)\chi_s H ,$$

where $\mathrm{d}y_s/\mathrm{d}t$ is the volume of solid that is formed per second and χ_s is the susceptibility of the solid which is given by the Curie–Weiss law. Since approximately

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0.5% of the liquid is converted into solid per millidegree of compressional cooling [6], dy_s/dt is about 2.2 $\times 10^{-4}$ cm^3/s for the fastest rate of compression in the experiment of SBA ($dT/dt = -12$ μK/s near T_c).

The rate $\dot{M}_\ell$ at which spins can be supplied to the solid from the normal liquid can be estimated by the expression

$$\dot{M}_\ell \equiv dM/dt \leqslant \chi_\ell H V_\ell / T_1 ,$$

$\dot{M}_\ell$ decreases as the polarization of the liquid increases. V_ℓ is the volume of the liquid present and the liquid susceptibility χ_ℓ can be obtained from the formula for the Pauli paramagnetism with $T_F \approx 180$ mK. T_1 is directly proportional to the magnitude of the magnetic field H [7]. If we assume that T_1 is a measure of spin relaxation processes that occur at the walls of the sample chamber, then it is inversely proportional to the ratio of the surface area of the chamber walls to the volume of the ^{3}He sample. By properly scaling the T_1 measurements of Corruccini and Osheroff [2] above T_c, we find that the ratio of $\dot{M}_s$ to $\dot{M}_\ell$ is

$$\dot{M}_s/\dot{M}_\ell \approx 2.2 \times 10^{-2} H(\mathrm{kG})/Z ,$$

where Z is the fraction of the total surface area of the walls that was not covered by solid ^{3}He. This ratio is approximately 0.62 when $H = 28$ kG and $Z = 1$. Our estimate for $\dot{M}_\ell$ assumed that all the spins are relaxing at a rate characterized by T_1. Even with such optimum conditions, $\dot{M}_s \gtrsim \dot{M}_\ell$ and the solid cannot form with equilibrium magnetization in high magnetic fields. For low fields solid with equilibrium polarization is formed both above and below T_c, and there is no change in the entropy. The order of magnitude of our above estimate for $H = 28$ kG is consistent with the fact that the effect is seen around $H = 20$ kG. Below T_c, T_1 decreases by three orders of magnitude. This implies that

$$\dot{M}_s/\dot{M}_\ell \approx 22 \times 10^{-6} H(\mathrm{kG})/Z .$$

Thus the liquid supplies the solid with a sufficient amount of magnetization below T_c.

If we assume that the magnetization in the normal liquid is transported by spin diffusion processes, then the rate at which magnetization is supplied to the solid can be written as follows:

$$\dot{M}_d \equiv dM/dt = \int j_d \cdot dA \approx D_{\mathrm{eff}} (\chi_\ell H/d) A ,$$

where j_d is the current density associated with spin diffusion, A is the cross-sectional area through which the spins diffuse, and d is the length through which the spins diffuse. Taking the Leggett–Rice effect [8–10] into account and using the measurements of Corruccini et al. [11], we find that

$$D_{\mathrm{eff}} \approx 1.7 \times 10^{-2}/(1 + H^2)\ \mathrm{cm^2/s} ,$$

and

$$\dot{M}_s/\dot{M}_d \approx 0.40\,(1 + H^2)\, d/A , \qquad (1)$$

with H in kG, d in cm, and A in cm^2. If we assume that the spins diffuse down the cell between two concentric tubes, then A is the area of the ring and is approximately 1.3 cm^2. For $H = 28$ kG, $\dot{M}_s \gtrsim \dot{M}_d$ if $d \gtrsim 4 \times 10^{-3}$ cm. We see from eq. (1) that for low fields the solid is formed with equilibrium magnetization above T_c since in this case $\dot{M}_s \ll \dot{M}_d$. This is consistent with the absence of the phenomenon in low fields.

Below T_c, the transport of magnetization is dominated by supercurrents j_{sc} which can be written as $j_{sc} = (\rho_s/\rho)\,\mu\rho v_c$, where ρ_s/ρ is the ratio of the superfluid density to the total liquid density, v_c is the critical velocity of the supercurrents, ρ is the number of atoms per unit volume, and μ is the magnetic moment of a ^{3}He atom. Assuming $v_c = 0.05$ cm/s, we find that

$$j_{sc} \approx 13\, \rho_s/\rho\ \mathrm{erg/cm^2\ kG\ s} ,$$

with $d = 0.1$ cm,

$$j_{sc}/j_d \approx 700(\rho_s/\rho)(1 + H^2)/H ,$$

where H is measured in kG. For $H = 28$ kG, $j_{sc}/j_d \approx 2 \times 10^4\ \rho_s/\rho$ which implies that solid is formed below T_c with equilibrium polarization.

The fact that the phenomenon was absent when the system was warmed is not inconsistent with our model since spin transport might be very fast in the highly polarized liquid formed by the melting solid. The depression of the melting curve with increasing magnetic field [6] implies that the melting pressure decreases with increasing solid polarization. Thus the step in the chart trace may be due to a sudden transition to the lower melting curve associated with the equilibrium magnetization of the forming solid. In agreement with experiment, our model predicts that larger backsteps should be found in the chart traces for higher compression rates because these have larger values of $\dot{M}_s$ and thus larger magnetization deficits. The abruptness of the drops may be related to the dependence of the spin relaxation mechanisms on the magnetization gradient as we infer from the work of Webb [12]. He found that at a certain critical tipping angle the spin relaxation process changes dramatically from exponential to nonexponential behavior. Adams [13] has suggested that the dependence of the position of the step on the cooling rate may indicate supercooling in the sense that solid with equilibrium magnetization cannot form directly on top of solid lacking such polarization.

In this paper we have proposed that the observations of SBA may be related to a change in the polarization of the forming solid which is due to a change in the spin relaxation mechanisms as the temperature decreases below T_c.

After preparing this manuscript, it came to our attention that Delrieu [14] has proposed a similar idea in which the rate of solid growth is limited by the spin relaxation rate in the liquid. According to his model, the abrupt drop in T_1 below T_c results in an increase in the rate of growth of the solid and an apparent decrease in the entropy.

One of the authors (C. Yu) gratefully acknowledges helpful discussions with Dr. D. D. Osheroff and Dr. M. C. Cross.

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