Effects of Magnetic Field on the "A" Transition in Liquid ^{3}He[†]

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In an applied magnetic field the "A" transition in liquid ^{3}He (at 2.7 mK on the melting curve) splits into two discrete transitions, occuring at different temperatures. This effect has been observed both in pressure-versus-time measurements in two different compressional cooling cells and in the attenuation of 10-MHz zero sound. The magnitude of the temperature splitting, in units of pressure along the melting curve, is $0.20H$ mbar for H in kOe. A third pressure-versus-time feature has been observed near A at high fields, but is not accompanied by an attenuation peak.

Osheroff, Richardson, and Lee,[1] measuring pressure as a function of time in a ^{3}He cell undergoing adiabatic compression at a constant rate, found an abrupt change in slope at a point these authors labeled "A". Similar observations subsequently were reported by Halperin, Buhrman, Webb, and Richardson[2] and by Johnson, Paulson, Giffard, and Wheatley,[3] while a series of NMR absorption measurements by Osheroff, Gully, Richardson, and Lee[4] furnished strong evidence that this feature was associated with a phase change in liquid ^{3}He. More recent experiments have found this transition to be characterized by striking features in specific heat,[5] ultrasonic attenuation,[6,7] and viscosity.[8]

The "A" transition takes place at a highly reproducible temperature—about 2.7 mK at the melting pressure. The change in slope of $P(t)$ represents a change in the thermal response of the compression cell, caused by a specific-heat anomaly[5] in the ^{3}He. Leggett[9] has proposed a model for the phase change at A based on a Bardeen-Cooper-Schrieffer[10] (BCS) pairing transition, in which the pairs form in triplet states (parallel spins) with odd relative orbital angular momentum l. BCS models also have been discussed by Varma and Anderson[11] and by Anderson.[12]

In this report we summarize some effects of applied magnetic field on the A transition. The data were obtained with the same compression cells used in the original work of Osheroff *et al.*,[1] as modified for NMR and ultrasonic attenuation experiments. The experimental techniques employed in these measurements are described in Refs. 1, 4, and 6.

The most dramatic effect of an applied magnetic field is the splitting of the A transition into distinct components, occurring at different temperatures. Although the field dependence of this splitting is well defined in terms of pressure intervals along the melting curve (see below), the field dependence of the absolute temperature of the transition has not been determined. The reason for this may be seen in Fig. 1: The highest temperature component of the transition ("A_1") occurs at a pressure along the melting curve which varies as $P_{A1}(0)-P_{A1}(H)=0.067H^2$ mbar for the applied field H in kOe. This H^2 dependence is thought to be a result of the lowering of the melting pressure by an applied magnetic field, resulting from spin ordering in the solid ^{3}He.[13] At the melting curve, the Gibbs free energy of the liquid is equal to that of the solid. An applied magnetic field will cause a change in the Gibbs free energy of the solid and, consequently, a shift in the melting pressure. A change in field δH leads to a change in the Gibbs function of the liquid $\delta G_L = V_L\delta P - S_L\delta T - M_L\delta H$ which must equal the change in the Gibbs function of the solid $\delta G_S = V_S\delta P - S_S\delta T - M_S\delta H$. If the temperature is held constant and M_L, the small magnetization associated with Pauli paramagnetism in the liquid is neglected, we obtain $V_L\delta P = V_S\delta P - M_S\delta H$, which, when integrated, yields the pressure change for a finite applied field H. Then for a constant susceptibility $M_S=\chi H$, the melting pressure at constant temperature varies as $-\frac{1}{2}\chi H^2/\Delta V$. Such a variation has been observed experimentally in P_{max}, the highly reproducible maximum pressure attainable in our compression cells.[1] As indicated in Fig. 1, we find that $P_{max}(0) - P_{max}(H) = 0.195H^2$ mbar for H in kOe. It is not clear that this P_{max} has physical significance, since recent experiments along the melting curve have observed higher pressures.[2,14] Our P_{max} is relevant to the present argument only if it occurs at the same temperature for different values of the applied field. It seems likely that this maximum pressure is determined by the onset of ordering in the solid and that the temperature of this onset is relatively insensitive to applied field. Using $\Delta P = -\frac{1}{2}\chi H^2/\Delta V$ and assuming

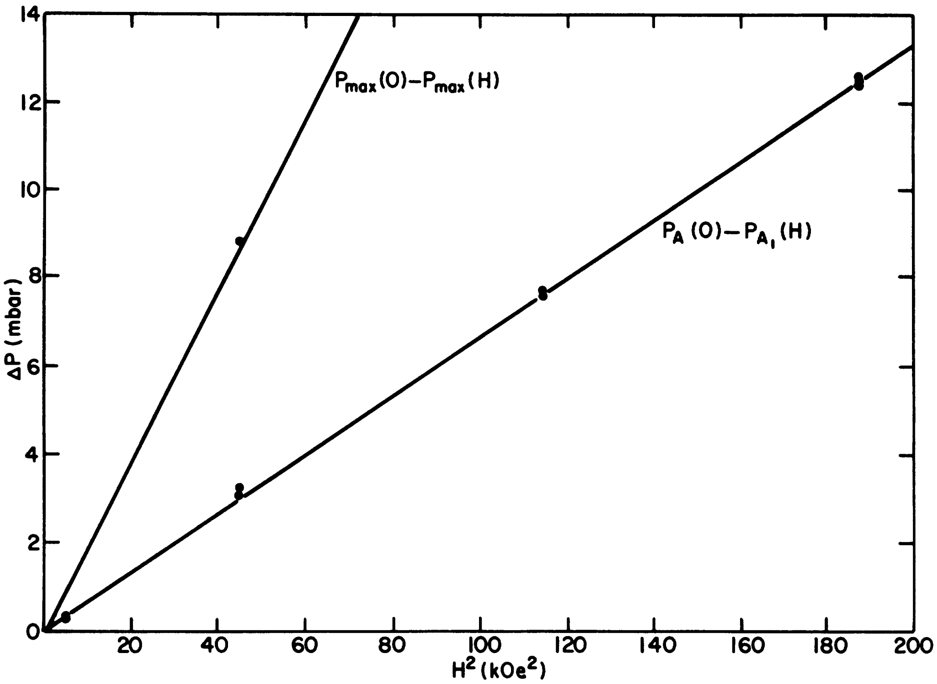

FIG. 1. Variation of P_{A_1} and P_{max} as a function of applied magnetic field. P_{max} is the maximum pressure attainable along the melting curve in our compression cells.

$$\chi=\frac{1}{3}\frac{N\mu^2}{k_B T^*}=\frac{4.6\times10^{-7}}{T-\Theta}\frac{\text{emu}}{\text{mole}}\quad\text{with } \theta<0,$$

we obtain $|\Delta P|<0.085H^2$ mbar at $T=2.7$ mK$\approx T_{A1}$, and $|\Delta P|<0.153H^2$ mbar at $T=1.5$ mK$\approx T_{P_{max}}$, for H in kOe. (1.5 mK is an upper limit on $T_{P_{max}}$, for $\Theta=0$, assuming that the melting-curve slope is given by the Clausius-Clapeyron equation with a constant solid entropy of $R\ln 2$.) Any such estimate is, of course, highly uncertain so close to the solid ordering temperature. Nevertheless, the available arguments suggest that less than a third of $\partial P_{A1}/\partial H$ is due to $\partial T_{A1}/\partial H$, and we cannot hope to determine even the sign of $\partial T_{A1}/\partial H$ until $P_{melt}(H, T)$ is better understood.

Our data for the A_1, A_2 splitting are shown as experimental points along the lines marked A_1 and A_2 in Fig. 2. The circles represent the pressures at which sudden changes in dP/dt were observed at each field. The squares represent instances for which ultrasonic attenuation peaks also were observed at the A_1 and A_2 transitions, allowing a somewhat more accurate determination of P_{A1} and P_{A2}. All of these data for A_1 and A_2 agree with a linear splitting in applied field, given by $P_{A2}(H)-P_{A1}(H)=0.20H$ mbar for H in kOe.

The two open-circle points in Fig. 2 represent a third feature first observed on the $P(t)$ curve near A during the recent attenuation experiments.[6] This feature, an abrupt *increase* in dP/dt during compression at a constant rate, is not understood at present. The filled circles near the same

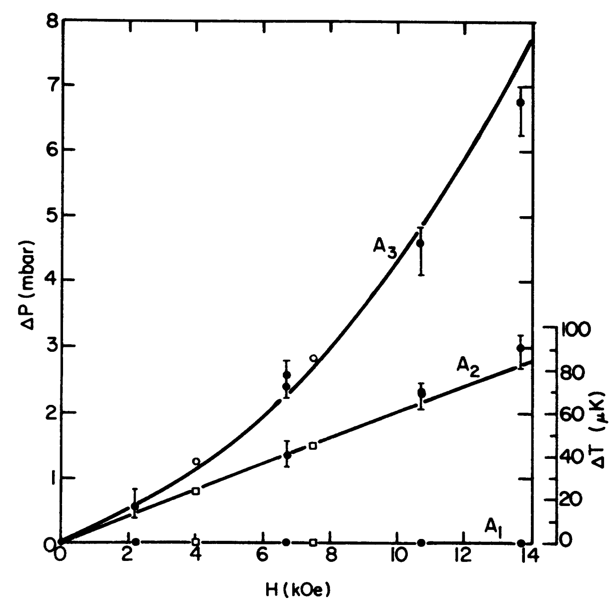

FIG. 2. Splitting of the A transition in an applied magnetic field. Filled-in symbols represent data from the earlier measurements (Ref. 1), and open symbols data from recent attenuation experiments (Ref. 6). Circles correspond to $P(t)$ features alone, while squares represent attenuation peak data as well. Bars indicate the uncertainty in determining the pressures at which $P(t)$ slope changes occur. The curves represent the calculation of Ambegaokar and Mermin (Ref. 15) fitted to our observed A_1, A_2 splitting. The ΔT scale assumes a local 33 mbar/mK slope for the melting curve.

curve in Fig. 2 represent a qualitatively similar feature barely discernable in some of the earlier data.

In Fig. 3 we have plotted typical $P(t)$ traces from the attenuation experiments, in fields of 4.0 and 7.5 kOe, during which the third pressure feature was seen clearly.[6] During all these observations, the sound transducer was being pulsed several times per second. The third feature was observed reproducibly and reversibly in these experiments, at various compression rates, and was not accompanied by an ultrasonic attenuation peak. We have normalized the traces for comparison by adjusting the t' scales to obtain a common slope at pressures just below P_{A_1}. Also shown are traces representative of the most sensitive of the earlier measurements[1,4] in magnetic fields of 6.7 and 10.7 kOe. The latter curves illustrate the presence of a third feature in some of the earlier data—also a sudden increase in dP/dt on compression, but with much smaller slope changes than those observed in the attenuation experiments.

It may be that the different geometries of the two liquid samples are in some way responsible for the large magnitude difference in slope changes. Another possibly significant difference between the earlier data at 6.7 and 10.7 kOe and the later data at 4 and 7.5 kOe is the fact that the later data were taken in the presence of a substantially higher heat leak, necessitating a high rate of solidification for adequate Pomeranchuk cooling. Following a suggestion of Halperin and Truscott,[15] we note that this rapid formation of solid will diminish n_S, the number moles of solid in equilibrium with the liquid, thereby reducing the effect of solid specific heat in the equation

$$\frac{dP}{dT} \approx \frac{Q_{refrig} - Q_{heat\ leak}}{n_L C_L + n_S C_S}.$$

This leads to an increased sensitivity of dP/dt to variations of the liquid specific heat.

Ambegaokar and Mermin[16] have worked out the consequences of the weak-coupling BCS theory for odd-l pairing near T_c and have shown that it is possible to interpret A_1 and A_2 within this frame-

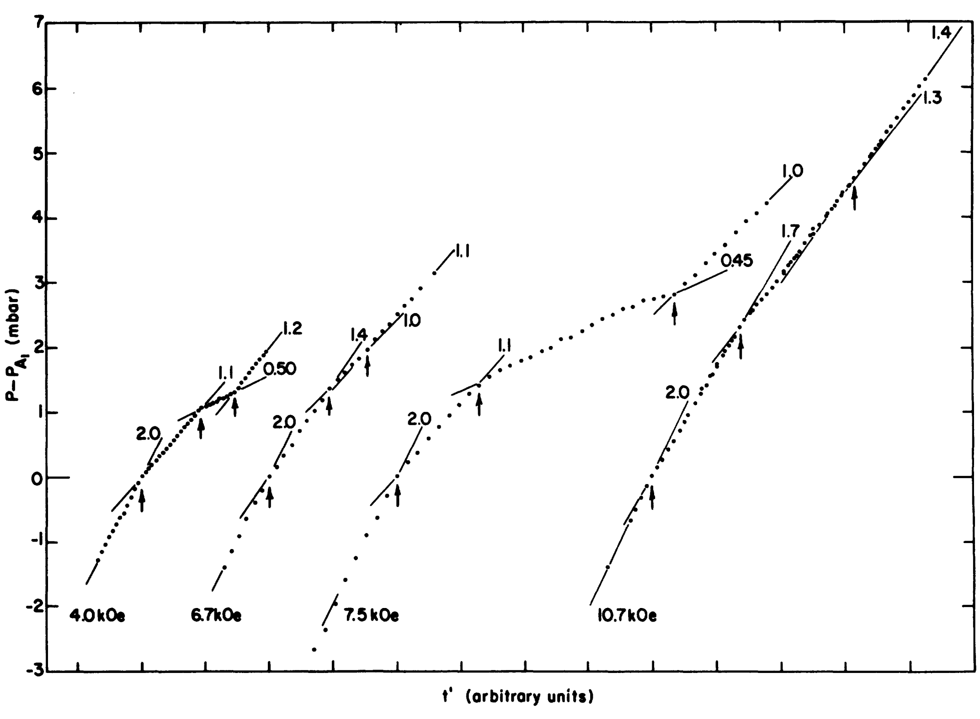

FIG. 3. Representative pressure-versus-time traces as a function of apparatus configuration and applied magnetic field. The 4.0- and 7.5-kOe traces are from the apparatus of Ref. 6 and the 6.7- and 10.7-kOe traces from that of Ref. 1. In order to compare the four sets of data, various t' scales have been used to normalize the data to a common slope for pressures just below P_{A_1} in each case. Time intervals between points range from 2 sec for the 4-kOe trace to 6 sec for the 6.7-kOE data. Additional points, taken while warming and plotted with the sign of t' reversed, have been added to the 10.7-kOe trace to indicate the reversibility of the third feature. Straight line segments have been added for comparison and are labeled with numbers proportional to their slopes. Arrows indicate A_1, A_2, and the third feature.

work.[17] The two transitions then may be understood as involving two weakly interacting Fermi populations with spins aligned parallel and antiparallel to the applied field, respectively. This calculation predicts a T_{A_1}, T_{A_2} splitting which is linear in applied field and symmetric about a field-independent T_c. Even though we cannot determine the field dependence of the absolute transition temperatures, our results do indicate that the splitting cannot be symmetric about a constant temperature. As discussed above, the melting-curve pressure corresponding to a constant temperature should vary as H^2. A comparison of Figs. 1 and 2 indicates that, while $P_A(0)-P_{A_1}(H)$ has a well-defined H^2 dependence, the splitting is large enough to give $P_A(0)-P_{A_2}(H)$ a dependence which is quite different. Clearly these variations are not symmetric about a P_c which varies as H^2. Recent work by Mermin and Stare[18] finds that if the weak-coupling assumption is dropped, the splitting need not be symmetrical.

The calculation of Ambegaokar and Mermin also predicted a third component for the A transition in a magnetic field ("A_3"), corresponding to a transition to an isotropic state. Ignoring the absolute temperature change, the predicted splitting is approximately

$$T_{A_1}-T_{A_3}\approx\frac{T_{A_1}-T_{A_2}}{2}\left[1+\left(1+\frac{16h^2}{\pi^4a^2}\right)^{\frac{1}{2}}\right],$$

where $h=\mu H/k_B T_A$ and $a=(T_{A1}-T_{A2})/hT_A$. Then, for $T_A\approx 2.7$ mK, $\mu/k_B\approx 0.078$ mK/kOe, $dP/dT \approx 35-40$ mbar/mK for this region of the melting curve, and using $P_{A2}-P_{A1}$ obtained from our experiments, we calculate the predicted pressure difference between the Ambegaokar-Mermin A_3 and the A_1 feature as a function of magnetic field,

$$P_{A3}-P_{A1}\approx 0.10H[1+(1+0.1H^2)^{\frac{1}{2}}] \text{ mbar}$$

for H in kOe. This equation yields the curve marked "A_3" in Fig. 2. Although there is reasonably good agreement between the splitting observed for our third pressure feature and that predicted for the A_3 transition, and although recent theoretical work by Wölfle[19] indicates that no comparable sound-attenuation peak is to be expected for A_3, there are, nevertheless, serious difficulties involved in identifying this third feature with A_3.

It is difficult to see how a sudden *increase* in dP/dt during compression could be consistent with such a transition. The Ambegaokar-Mermin calculation predicts a sudden increase in specific heat on cooling through A_3—qualitatively like that at A_1 and A_2—which would imply a *negative* d^2P/dt^2 on compression. A model seeking to explain the third pressure feature in terms of specific heat would have to include an abrupt decrease in specific heat on cooling through this feature.

Current indications, based on the observed temperature-independent susceptibility[4,9] between A and B and the shape of the sound-attenuation peaks[6,19] near A, are that the anisotropic energy gap is an important feature of the phase below the A transition in liquid ^{3}He. Thus the observed third pressure feature is probably not associated with a transition to a phase with an isotropic gap and may not result from any phase transition whatsoever. It would be desirable to obtain further experimental data on this phenomenon.

In conclusion, we may state that the twofold splitting of the A transition in a magnetic field, which was observed both in pressure-versus-time experiments and sound-attenuation experiments, is consistent with the occurrence of odd-l pairing in liquid ^{3}He. The recently observed third pressure feature remains to be explained.

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