Specific Heat of Liquid ^{3}He †

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In this paper we report specific heat measurements of liquid ^{3}He in the temperature range from 0·054° to 0·3° K, and at pressures from saturated vapour pressure to pressures above the minimum in the melting curve. Previous measurements of Brewer, Daunt and Sreedhar[1], extending to 0·085° K, indicated that the liquid specific heat appeared to be proportional to the temperature in the region below about 0·1° K, which is the behaviour predicted from the Fermi liquid theories[2, 3, 4] and the theory of Goldstein[5], near 0° K.

At the time our measurements were undertaken several investigators had indicated that if ^{3}He were, indeed, a Fermi liquid, a co-operative transition to a superfluid phase should occur at about 0·08° K[6, 7]. In going from the normal to the superfluid state, a discontinuous increase in the specific heat of about a factor of two was predicted[6]. This would make the specific heat a very sensitive test for such a transition. No indication of a transition was found in any of our measurements. Measurements made at the University of Illinois have now established that at saturated vapour pressure no transition is present in the liquid down to 0·008° K[8, 9].

The results at saturated vapour pressures are shown in *Figure 1* along with the data of Anderson *et al.*[9]. It is seen that there is no evidence of any co-operative transition. In the region near 0° K the theories of Landau[2, 3] and of Brueckner–Gammel[4] give $C = C_f m^*/m$, where C_f, the specific heat of an ideal Fermi gas of mass m, is proportional to T; and m^*/m, the ratio of the effective mass of ^{3}He to the mass of an ^{3}He atom, is a constant. The combined data confirm the approximate behaviour predicted; however, some curvature seems to remain in the C vs T curve to very low temperatures. A straight line drawn through the origin and our lowest temperature points in *Figure 1* gives a value of $m^*/m = 2{\cdot}19 \pm 0{\cdot}13$. However, the limiting low temperature value of m^*/m from the lower temperature data of Anderson *et al.*[9] is given by them as $2{\cdot}82 \pm 10$ per cent. The value of C/T corresponding to the above value of m^*/m is in good agreement with the spin specific heat theory of Goldstein[5]. The results at elevated pressures, along with the smoothed curve of the saturated vapour pressure data, are shown in *Figure 2*. It is seen that in the low temperature region the specific heat increases with pressure, in agreement with the measurements of Brewer, Daunt and Sreedhar[1]. Our measurements agree reasonably well with recent results of Brewer and Keyston[10], and the data of Anderson *et al.*[9], at lower temperatures, is seen to join on well to ours.

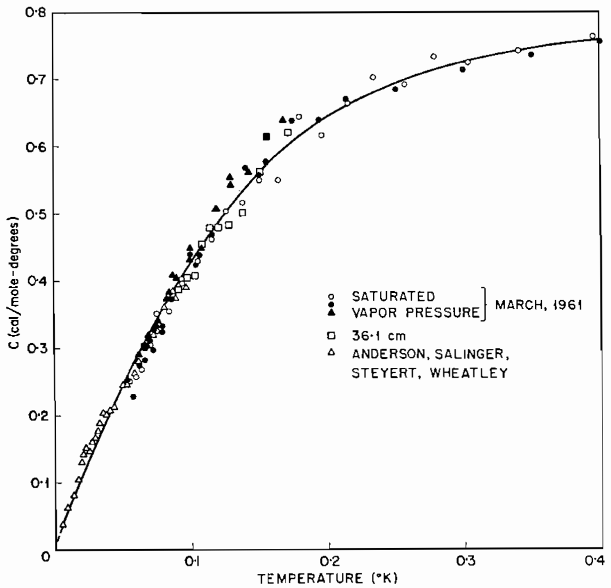

Figure 1. The specific heat of liquid ^{3}He *at saturated vapour pressure vs temperature. The results of Anderson et al. at a pressure of* 0·12 atm *are also shown*

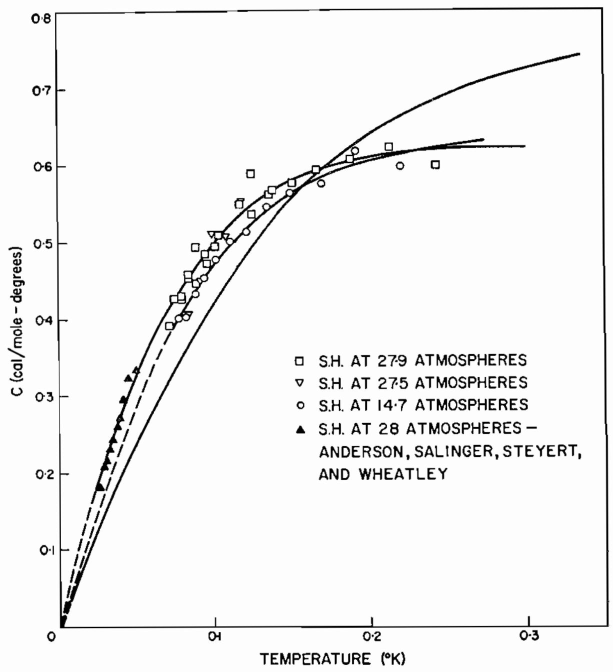

Figure 2. The specific heat of liquid ^{3}He *vs temperature at several pressures. The lowest curve (without points) is the saturated vapour pressure curve from Figure 1*

By combining all the specific heat data we have been able to

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obtain a reasonable extrapolation to 0° K. The entropy at temperature T was then calculated from the equation

$$S = \int_0^T \frac{C}{T}\,dT$$

The entropy values obtained in this way are shown in *Figure 3.* Above 0·23° K the results can be compared with the entropy values of Weinstock, Abraham and Osborne[11], who calculated the liquid entropy from the entropy of the vapour and the heat of vaporization at 1·5° K, and the liquid specific heat values from 0·23° to 1·5° K. The agreement is excellent. At saturated vapour pressure and 0·23° K we obtain for the liquid entropy 0·95 ± 0·04 cal/mole-deg.; Weinstock *et al.* report 0·96 ± 0·03 cal/mole-deg.

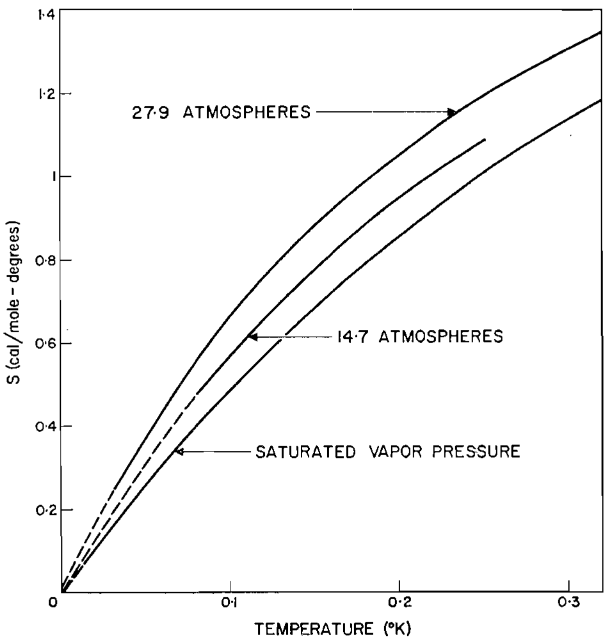

Figure 3. The entropy of liquid ^{3}He *vs temperature at three pressures*

At the minimum in the melting curve, according to the Clapeyron equation, the entropies of the solid and liquid are equal, and since the lattice entropy of the solid is very small at this temperature, the entropy of the solid should be Rln2, the entropy of the unaligned nuclear spin system. Measurements of the nuclear susceptibility of the solid[12] show classical Curie law behaviour down to temperatures below that of the melting curve minimum. From the entropy curve at 27·9 atm and the entropy of compression values of Lee, Fairbank and Walker[13], we obtain 1·35 ± 0·04 cal/mole-deg. for the entropy at the melting curve minimum, in good agreement with the expected value of Rln2.

Measurements of the expansion coefficient α of liquid ^{3}He have also been made in order to clarify the disagreement between recent measurements from other laboratories[10, 14]. From measurements of the dielectric constant, Rives and Meyer[14] indicated that the expansion coefficient of the liquid becomes positive at a pressure above 20 atm and at temperatures below 0·1° K. Brewer and Keyston[10], on the other hand, find α to be approximately proportional to T and negative in this same temperature and pressure range. With the method of Brewer and Keyston[10] we measured the change in temperature ΔT resulting from an adiabatic change of pressure Δp and then calculated α from the equation

$$\alpha = \frac{C}{TV}\left(\frac{\Delta T}{\Delta p}\right)_s$$

The values of the expansion coefficient obtained in the range of temperature 0·07° to 0·135° K and at average pressures from 21·3 to 27·7 atm are in good agreement with those of Brewer and Keyston (the estimated error is about 50 per cent in both sets of measurements). In every case heating was observed on expansion and cooling on compression, indicating a negative α.

Preliminary measurements have been made of the specific heat of solid ^{3}He at temperatures down to 0·085° K and pressures up to 70 atm. The specific heat was found to be very small (below 3×10^{-3} cal/mole-deg.) in the temperature range 0·085° K to 0·16° K, with no indication of the antiferromagnetic transition suggested by nuclear susceptibility measurements[12]. This is in agreement with the preliminary specific heat measurements reported by Edwards *et al.*[15]. The explanation for this apparent inconsistency between the specific heat and susceptibility behaviour is not understood. We are investigating the specific heat at higher magnetic fields in view of the fact that the susceptibility measurements were made in a field of 900 G while the specific heat measurements were carried out in the earth's magnetic field.

References

[1] Brewer, D. F., Daunt, J. G. and Sreedhar, A. K. *Phys. Rev.* 115 (1959) 836
[2] Landau, L. *J. exp. theor. Phys.* 30 (1956) 1058
[3] Landau, L. and Lifshitz, E. *Statistical Physics.* 1958. Addison Wesley
[4] Brueckner, K. A. and Gammel, J. L. *Phys. Rev.* 109 (1958) 1040
[5] Goldstein, L. *Phys. Rev.* 96 (1954) 1455; 112 (1958) 1465
[6] Brueckner, K. A., Soda, T., Anderson, P. W. and Morel, P. *Phys. Rev.* 118 (1960) 1442
[7] Emery, V. S. and Sessler, A. M. *Phys. Rev.* 119 (1960) 43
[8] Anderson, A. C., Salinger, G. Z., Steyert, W. A. and Wheatley, J. C. *Phys. Rev. Ltrs* 6 (1961) 331
[9] Anderson, A. C., Salinger, G. Z., Steyert, W. A. and Wheatley, J. C. *Phys. Rev. Ltrs* 7 (1961) 295
[10] Brewer, D. F. and Keyston, J. R. G. *Nature, Lond.* 191 (1961) 1261
[11] Weinstock, B., Abraham, B. M. and Osborne, D. W. *Suppl. Nuovo Cim.* 9 (1958) 310
[12] Adams, E. D., Meyer, H. and Fairbank, W. M. *Helium Three,* p. 57. 1960. Ohio: Ohio State University Press
[13] Lee, D. M., Fairbank, H. A. and Walker, E. J. *Phys. Rev.* 121 (1961) 1258
[14] Rives, J. E. and Meyer, H. *Phys. Rev. Ltrs* 7 (1961) 217
[15] Edwards, D. O., Baum, J. L., Brewer, D. F., Daunt, J. G. and McWilliams, A. S. *Helium Three,* p. 126. 1960. Ohio: Ohio State University Press