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SPECIFIC HEAT OF He^3 UNDER PRESSURE*

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We have measured the heat capacity of a mixture of He^3 and powdered cerium magnesium nitrate (CMN) from 0.02°K to temperatures as high as 0.1°K at pressures of 0.12, 1.10, 3.4, 6.1, 11.8, 21.1, and 28.0 atm and for pressures greater than that of the minimum in the melting curve, $P_{\rm min}$, at external pressures of 30.7, 32.8, and 34.8 atm. The specific heat seems to be linear in T below temperatures of about 0.03°K only at the lowest pressures, but at higher pressures it is possible that the linear temperature dependence of the specific heat characteristic of a Fermi liquid has not been developed by 0.02°K. Assuming a Fermi liquid behavior at 0.03°K, we obtain at zero pressure a ratio of the specific heat to temperature which is considerably greater than that deduced from earlier experiments[1-3] and predicted by Brueckner and Gammel,[4] but in agreement with the theory of Goldstein.[5] We also deduce a lower limit for the isobaric expansion coefficient. We find no discontinuity in specific heat down to 0.02°K for the full pressure range in the liquid although the theories[6,7] of cooperative transitions in He^3 predict an increasing transition temperature with effective mass and hence with pressure. We find that the liquid phase of He^3 at pressures above $P_{\rm min}$ and at low temperatures has a smaller specific heat and a reduced thermal boundary resistance relative to that at somewhat lower pressures. We were able to measure the thermal boundary resistance at various pressures in a more restricted temperature range than the specific heat and found that it decreased slowly as pressure increased. Details of these measurements will be given in a subsequent publication. The measurements on the solid revealed a small specific heat increasing as the temperature decreased below 0.036°K, indicating that the exchange interaction is much smaller than that predicted by Bernardes and Primakoff.[8]

The cell containing the mixture of He^3 and CMN had the same geometry as that reported previously,[1] except that there was 0.585 g of CMN in the cell and that the heater consisted of a bifilar lead of 0.002-inch diameter manganin wire 6 inches long, the ends of which were silver soldered to 0.004-inch diameter copper leads. These joints were inside the cell. The Epibond 100A[9] plug, which closed the cell, was sealed by Epibond 121 which is nonmagnetic.[10]

The magnetic susceptibility of the cell was carefully measured in the 0.3-1°K temperature range both with and without CMN inside. We were able to calibrate the thermometer to within 2% and to deduce that magnetic effects caused an error of less than 1.5%.

The pressure was applied to the He^3 using a stainless steel Toepler pump. The pressure was set using a dead-weight tester[11] and monitored using a Helicoid gauge.[12] The hydrostatic pressures due to mercury and oil in the pressure system were measured and corrections were applied to the dead-weight pressures. The pressure was held constant to within 1% during a run.

The quantity of He^3 in the cell below 1°K was measured to be 0.0080 ± 0.0002 mole at 0.12 atm. The He^4 content was less than 4 parts in 10^5 and the tritium decay rate in the cell was less than 300 disintegrations/sec.

The low temperatures were produced in essen-

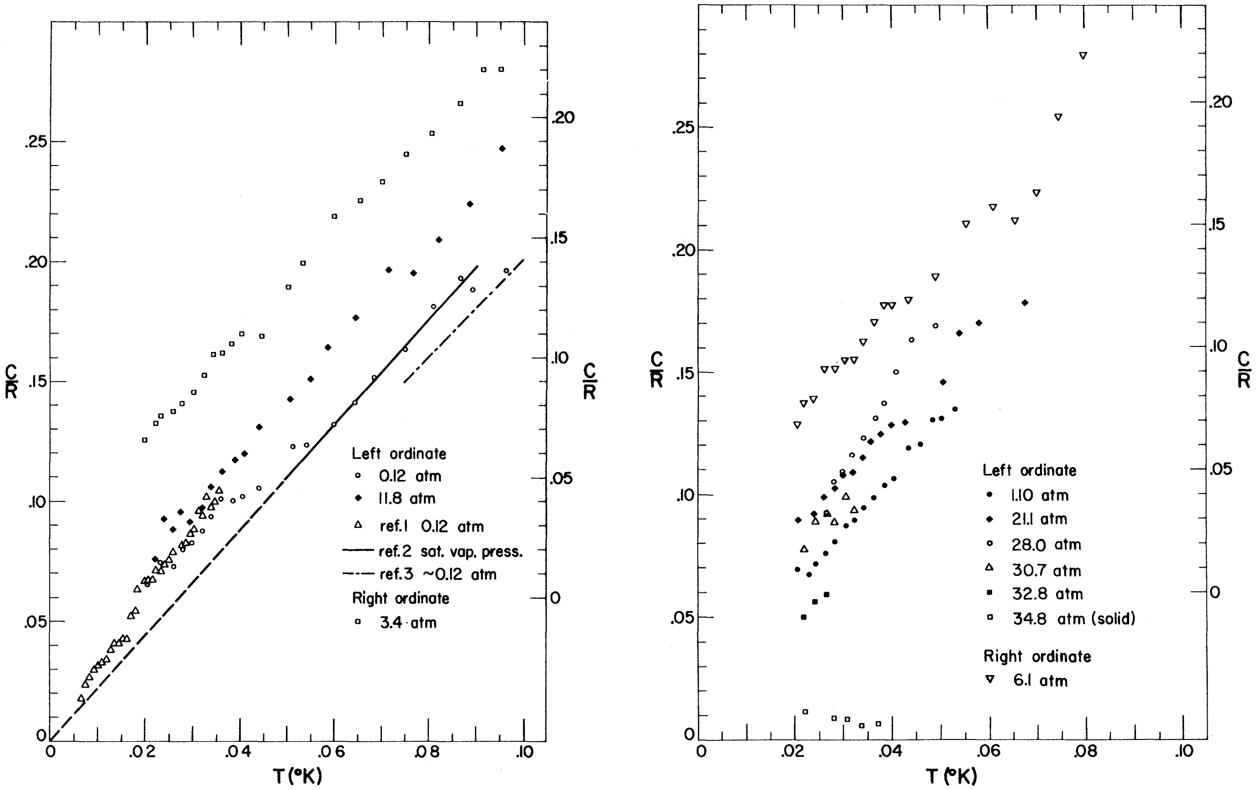

FIG. 1. Ratio of specific heat, C, to gas constant R (=8.317 joules/mole K°) for He^3 under pressure. The right ordinate is displaced upward in order to display the data better. Above 29 atm, the pressures indicated were those in the external system.

tially the same way as previously described.[1,13] Temperatures down to 0.02°K were obtained when the cell was thermally coupled directly to the refrigerator using copper "coil foils."[13] Temperatures down to 0.04°K were obtained when a lead switch was inserted between the cell and the refrigerator.

The data for the heat capacity were taken by the method of reference 1. With the tight thermal coupling, the best data were obtained around 0.03°K; and with the lead switch, the best data were obtained from 0.06 to 0.08°K.

The ratio of the specific heat, C, to the gas constant, R, is displayed as a function of temperature, T, for various pressures in Fig. 1. In reducing the heat capacity data to C/R, we assumed the volume of the He^3 in the cell to be constant. The number of moles in the cell was determined from the molar volumes of Sherman and Edeskuty,[14] extended to 0°K by extrapolating the density data of Lee, Fairbank, and Walker[15] to 0°K and higher pressures. The molar volume ratios used for the reduction of the data are given in Table I. For pressures greater than $P_{\min}$, the molar volume was assumed to be that of the liquid just before the filling tube plugged. This assumption is probably not precise, but it does not lead to errors in excess of 5% in C/R.

The data of reference 1, plotted on Fig. 1, have been corrected for an incorrect temperature calibration resulting from the magnetism[10] of SC-13

Table I. Density ratios of He^3 near $T = 0$°K.

P (atm)	$\rho/\rho_{0.12}$ [a]	P (atm)	$\rho/\rho_{0.12}$ [a]
0.12	1.000	21.1	1.338
1.10	1.033	28.0	1.393
3.4	1.094	30.7[b]	1.422
6.1	1.148	32.8[b]	1.437
11.8	1.234	34.8[b]	1.452

[a] $\rho/\rho_{0.12}$ is the ratio of the density of He^3 at pressure p to that at 0.12 atm near $T = 0$°K. The molar volume of He^3 at 0.12 atm is 36.73 cm^3/mole. $\rho/\rho_{0.12}$ is used to reduce the heat capacity data to specific heats.

[b] This is the pressure at which the He^3 plug formed.

flexible silver micropaint[16] used to join the heater to the copper leads inside the cell. Since the same coil system and geometry were used in both reference 1 and this experiment, the temperature calibration in reference 1 was assumed to differ from the present one only by the ratio of the masses of CMN. Both the corrected calibration constant of reference 1 and that in the present experiment agree within 5% with that calculated from the known geometry, galvanometer flux sensitivity, and properties of CMN.

A lower limit on the values of C/RT and m^*/m near $T = 0°\text{K}$ was obtained by drawing the best straight line between the data near 0.03°K and the origin. The results for various pressures are displayed on Fig. 2. There is no experimental justification for this procedure at the higher pressures. At zero pressure we find that $C/RT = 2.78\ (\text{K}°)^{-1} \pm 10\%$ and $m^*/m = 2.82 \pm 10\%$, using the formula

$$\frac{m^*}{m} = \frac{C}{RT}\frac{\hbar^2}{mk}\left(\frac{3N}{\pi V}\right)^{2/3}, \tag{1}$$

where all symbols have their usual meaning.[1] At these temperatures $(C_p - C_v)/C_p$ is negligibly small. This value of m^*/m is to be compared with the extrapolation from 0.085°K of reference 3 giving $m^*/m = 2.00 \pm 0.05$, and with the extrapolation from 0.054°K of reference 2 giving $m^*/m = 2.19 \pm 0.13$. These are consistent with the curve of C/R vs T bending in the region of 0.03-0.04°K, the same temperature above which the thermal conductivity began to deviate from the Fermi liquid temperature dependence.[17] The theoretical value of m^*/m of Brueckner and Gammel[4] is 1.84. Summing the spin and nonspin contributions to the specific heat calculated by Goldstein,[5] we find $C/RT = 2.74\ (\text{K}°)^{-1}$, which corresponds to $m^*/m = 2.78$.

Below 25 atm, the limiting values of C/RT are linear in p and may be used to obtain the isobaric expansion coefficient. Using the formula, valid near $T = 0°\text{K}$,

$$\frac{\partial \alpha_p}{\partial T} = -\frac{R}{V}\left[\frac{\partial}{\partial p}\left(\frac{C}{RT}\right)\right]_T, \tag{2}$$

where $\alpha_p = (1/V)(\partial v/\partial T)_p$ and v is the molar volume, we find at zero pressure

$$-\partial \alpha_p/\partial T = 0.08\ (\text{K}°)^{-2}, \tag{3}$$

as a lower limit. Brueckner and Atkins[18] obtain $0.076\ (\text{K}°)^{-2}$ for this quantity, using results which gave the effective mass incorrectly. Goldstein[5] predicts $0.103\ (\text{K}°)^{-2}$. Brewer and Daunt[19] calculate from their data $0.105\ (\text{K}°)^{-2} \pm 25\%$. Recently, Rives and Meyer[20] found $\alpha_p = -(0.12 \pm 0.02)T$ between 0.04 and 0.08°K at 0.18 atm.

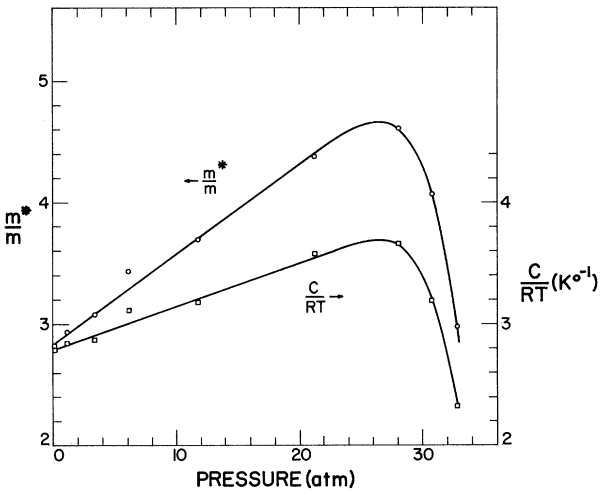

FIG. 2. Variation of lower limits of m^*/m and C/RT with pressure. The points on this graph were obtained by taking the slope of the best straight line through the data near 0.03°K and the origin. Below 25 atm, the slopes of the curves are $(d/dp)(m^*/m) = 0.074\ \text{atm}^{-1}$ and $(d/dp)(C/RT) = 0.036\ (\text{atm}\ °\text{K})^{-1}$.

We measured the specific heat and thermal boundary resistance of liquid He^3 at pressures above p_{min} and at temperatures of 0.02°K and somewhat above by applying pressures of 30.7 and 32.8 atm near 1°K and then cooling through the solid and back into the liquid. In this region both the specific heat and the thermal boundary resistance are anomalously low, and the specific heat had the opposite pressure dependence from that at somewhat lower pressures. During measurements taken when a plug formed in the filling tube at a pressure of 32.8 atm, the specific heat became very high at temperatures higher than 0.030 ± 0.001°K, indicating the liquid-solid phase transition. For an external pressure of 34.8 atm, we found no evidence of two-phase equilibrium between 0.017°K and 0.036°K, and hence, we conclude that our specific heat measurements for these conditions were for the solid only. The results of Sydoriak, Mills, and Grilly[21] indicate that, if the molar volume in the cell were the same as that in the liquid just before solidification commenced, it would be impossible to have only solid He^3 in the cell. Hence, we conclude that during the formation of the plug in the capillary leading to the cell, additional He^3 enters the cell. This effect can be observed in the external pressure system.

The results of specific heat measurements of solid He^3 for an external pressure of 34.8 atm are displayed on Fig. 1. Although the data are not precise enough to determine the temperature dependence of the specific heat, the specific heat does decrease as T increases. The theory of Bernardes and Primakoff[8] predicts, for a body-centered cubic crystal, that $C/R = 3J^2/k^2T^2$, where J/k is the exchange energy in temperature units. Assuming that the data fit a $1/T^2$ law, we find an average value for $|J/k|$ of 0.0015°K. This is about 10 times lower than the value of J/k ($= -0.02$°K) calculated in reference 8 for a face-centered cubic crystal. Since in the neighborhood of the melting curve and at low temperatures the entropy of the solid is unexpectedly high and the entropy of the liquid is unexpectedly low, it is not surprising that the predicted[8,22] maximum in the melting pressure curve has not yet been observed. The rate of heat transfer between solid He^3 and the walls is comparable to that of the liquid and the walls.

The pressure of the minimum in the melting pressure curve was measured several times by observing the sudden increase in temperature of the CMN when the He^3 pressure decreased slowly through P_{min}, and the He^3 plug broke. We find $P_{\text{min}} = 29.0 \pm 0.1$ atm. This agrees, within experimental error, with $P_{\text{min}} = 28.91 \pm 0.02$ atm obtained by Sydoriak, Mills, and Grilly[21] and $P_{\text{min}} = 29.1 \pm 0.1$ atm obtained by Lee, Fairbank, and Walker.[15] It is slightly lower than the $P_{\text{min}} = 29.3 \pm 0.1$ atm obtained by Baum, Brewer, Daunt, and Edwards.[23]

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