New Data on the Heat Capacity of Liquid $^3$He

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Recent heat capacity measurements on liquid $^3$He by Haavasoja have shown much smaller values than previous measurements by Wheatley. We have measured $P_V(T)$ from which we can derive values for $\partial C_v/\partial V$. A comparison with values of $\partial C_v/\partial V$ obtained from the actual heat capacity measurements shows agreement between our data and those from the heat capacities of Wheatley but disagreement with those from the heat capacities of Haavasoja. This suggests that the large discrepancy between the two sets of heat capacities originates with a problem in the data of Haavasoja.

The low-temperature heat capacity of liquid $^3$He has been measured a number of times. The results are well described by:

$$C_v/R = \gamma(v)T$$

where $C_v$ is the molar heat capacity, $R$ is the gas constant and $\gamma$ is the volume-dependent proportionality constant. This simple temperature dependence is also the prediction of Fermi-liquid theory.\(^7\) From the value of $\gamma$ obtained from experiment comes one of the most important parameters of Fermi-liquid theory, the effective mass, $m^*$, of the quasiparticles.

The previously accepted values for $\gamma(v)$, as derived from several earlier measurements, have been given by Wheatley.\(^6\) They vary from a value of 3.00 K$^{-1}$ at low density (zero pressure) to a value of 4.85 K$^{-1}$ at high density (34.36 bar). These values of $\gamma$ correspond to values of $m^*/m$ (where $m$ is the mass of the $^3$He atom) of 3.01 and 6.22, respectively. However, recent, precise measurements by Haavasoja\(^7\) have yielded quite different results: values of $\gamma$ of 2.11 K$^{-1}$ and 3.56 K$^{-1}$ at the same pressures as above, corresponding to $m^*/m$ values of 2.12 and 4.56, respectively. These differences are much greater than the combined uncertainties of the two measurements.

In order to resolve the discrepancies between the two sets of heat capacity data we have developed an experiment that determines the volume derivative of the heat capacity.
The starting point for our measurement comes from the determination of the pressure of the liquid at constant volume as a function of temperature, \( P_V(T) \). By simple thermodynamic arguments one can show that, in the region where Eq. 1 is valid, the temperature dependence of the pressure is

\[
P_V(T) = P_0 + \frac{1}{2} \left( \frac{\partial (C_V/T)}{\partial V} \right)_T T^2
\]  

(2)

By comparing the volume derivative of \( C_V \) measured in this way with that obtained from the direct \( C_V \) measurements, we will be able to say which measurement of \( C_V \) is correct.

The experimental arrangement consists of three parts: the liquid \(^{3}\)He sample cell containing cerium magnesium nitrate (CMN) which is used for both refrigeration and thermometry; a very sensitive capacitive pressure gauge\(^8\) which can resolve at least \( 10^{-5} \) bar over the entire 30 bar range of the experiment; and a low-temperature valve\(^9\) that isolates the sample \(^{3}\)He from external pressure fluctuations. The pressure gauge and the valve are thermally anchored to the mixing chamber of our dilution refrigerator and connected to the sample cell by long, thin capillary lines. The volumes of the gauge, the valve and their connecting lines are negligible compared to the sample volume. The sample cell is connected to the mixing chamber by a Sn heat switch. To reach the lowest temperatures (~2 mK) the cell is precooled to about 12 mK by the dilution refrigerator, the heat switch is opened, and the CMN in the sample cell is demagnetized. At that point a set of coils on the outside of the cell measures the susceptibility of the CMN to determine the temperature. The constants \( C \) and \( M_0 \) in the equation \( T = C/(M-M_0) + \Delta \) (where \( M \) is the reading of the susceptibility bridge) are determined by calibration against a germanium thermometer from 0.3 to 1.0 K. The constant \( \Delta \) is determined by calibration against the superfluid transition temperature, \( T_c \), \(^7\) at high pressures.

Figure 1 shows the results of measurements at 6 different pressures plotted versus \( T^2 \) to display the behavior expected from Eq. 2. Clearly, the \( T^2 \) behavior is closely followed up to 30-35 mK, thus confirming the validity of
Eq. 1. The slopes of these curves are the quantities to be compared to the volume derivatives of the experimental heat capacities. This comparison is made in Fig. 2, where the derivatives of the experimental data have been converted to units of microbar (mK)-2. Error bars of ± 10% are included with the derivatives of the data of Wheatley to reflect our estimate of the uncertainty of these numbers. The data of Haavasoja are much more precise and we have not included error bars for this data. The points shown in the figure are the results of the present experiment; the open circles are from the data shown in Fig. 1 and the closed circles are from various other runs on the same apparatus. Clearly, our points agree well with the derivatives of the heat capacity data of Wheatley but not with that of Haavasoja. This is convincing evidence that the Wheatley $C_V$ data are correct and that the $C_V$ data of Haavasoja are incorrect due to some systematic error. The most likely source of error is in the temperature scale for the experiment. Haavasoja is able to relate his temperature scale to a recent one used by Paulsen et al. by using the line of the superfluid phase transition temperature. The difference he finds is not enough to explain all the difference between the two sets of heat capacity measurements but it would greatly reduce the discrepancy. The difference in temperature scales is just about the right amount to bring the derivative of Haavasoja's heat capacity data into agreement with the present experiment, however. This strongly suggests that there is a problem with the temperature scale used by Haavasoja.
REFERENCES

FIGURE CAPTIONS

Fig. 1: Results of $P_v(T)$ for liquid $^3$He at six pressures plotted versus $T^2$.

Fig. 2: Comparison of values of $-(1/2)\partial^2 p/\partial T^2$ from the present experiment (open and closed circles) with the values of $\partial(C_v/T)/\partial v$ from heat capacities of Wheatley and Haavasoja (Ref. 6,7).