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DOES FERMI LIQUID THEORY APPLY TO He^3 ?

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Abstract

Examination of the experimental data on the low-temperature specific heat of liquid He^3 indicates that there is no evidence for the linear form expected on the Fermi liquid theory, and considerable evidence for the form $T \ln T$.

MANY of the properties of liquid He^3 have come, as lower and lower temperatures have become available, to fit increasingly well with the predictions of Landau's Fermi liquid theory [1]. This theory assumes that the properties of a fluid system of Fermions (in the absence of pair condensation) are qualitatively equivalent to those of a weakly-interacting Fermi gas, requiring only quantitative renormalization for the effects even of strong interactions. He^3 is in many ways the most straightforward test case for the theory, being free of the complications of charge and lattice effects of the electron gas in metals, and of charge and size effects of nuclear matter. The preceding paper [2] shows that the susceptibility and spin diffusivity agree well with the constant and T^{-2} behaviors expected.

On the other hand, the situation has not been so clearcut with respect to other properties; we concern ourselves here with the specific heat, of which possibly as many and as careful measurements exist as of any other property. From the start the supposed coefficient in the expected linear variation has been found to change with each succeeding measurement.

Examination of Fig. 11 of the preceding paper [2] suggested that the plot shown in Fig. 1 might bring out the actual significance of the data. We plot here the specific heat $C_{(p)}$ divided by nRT (n the number of moles, R the gas constant), against the absolute temperature T on a logarithmic scale. All the measurements are at low constant pressure or at saturated vapor pressure; no significant difference is observed for any pressure below 1 atm. What higher pressure data exist are qualitatively similar but not as complete; in particular none indicate a linear law. It is seen that the data given here (we will discuss them more fully below) are entirely inconsistent with a linear law $C/T = \text{const.}$ for any range yet measured, which would appear as a horizontal straight line on this graph. The most plausible fit is the expression (coefficients accurate to ~ 10 per cent):

$$C/nRT = 1.00 + 0.50 \ln 1/T. \quad (1)$$

This deviates from the data seriously only in the region $> 0.2^\circ\text{K}$, which is where those properties which have Fermi liquid behavior also tend to deviate strongly. There is no known small

theoretical parameter which would suggest a radical change in behavior at a much lower temperature. The data shown on the curve are: (a) One point of Abraham, Osborne and Weinstock [3] at 0.25°K, to show the smooth fit to the older, conventional data; (b) The data of Anderson, Reese and Wheatley [4], which are restated in detail in ref. [2] and some data added. We show typical rather roughly averaged points rather than copying their smoothed curves. This data covers the widest range and is most complete, overlapping all others except ref. [2]. Basically our case rests on it, but it agrees well enough with data taken by other groups in all cases. The most

FIGURE 1

Collected data for C/nRT vs. $\ln T$ at low temperature and low pressure.

A.O.W.: Abrahams *et al.* [3]; A.R.W.: Anderson *et al.* [4]; S.Z.F.: Strongin *et al.* [5]; A.A.B.W.: Abel *et al.* [2]. The straight line is equation (1) of the text. All points except at the higher temperatures have errors of order 5 per cent.

likely source of systematic error is that in all of this work the He^3 was in more or less intimate contact with Ce-Mg nitrate, which was used also for a temperature scale. An entirely unsuspected flaw in the T scale or source of specific heat in this substance, or both, could falsify all this data. (c) Smoothed points of Strongin *et al.* [5] over the whole range they measured. Good agreement except at 0.06°K, where the authors' system was at its limit, is seen. (d) We do not plot Brewer and Keyston's [6] data, which extends over roughly the range of ref. [5] and a bit below. That data resembles both (b) and (c) but is uniformly 5-10 per cent lower. Since relative values within the same set of data are more accurate than absolute comparisons, it was felt that including that data would confuse Fig. 1 without seriously modifying the picture. (e) The most recent paper, [2], quotes a firm value only for the point at 0.015°K. We also show several of the raw data points which include an unknown amount of CMN and heater capacity. That at 0.020°K was taken above the surrounding system temperature and may include a heat loss error; the rest partake of the general upward slope.

Three interpretations suggest themselves. The first, that of experimental error, has been discussed adequately above. The second, that lower temperature data may settle down to a linear law, is dubious in the absence of any theoretical reason for such a change in behavior but of course is by no means excluded. The third is an actual failure of Fermi liquid theory. Such a

failure need not necessarily invalidate the whole structure of the theory; it may merely be that the self-energy due to exchange of some collective excitation has an unexpectedly singular form.

It may be noted that (1) does not violate the Third Law but does increase the entropy at low temperatures noticeably: it gives

$$S(T)/nR = 0.50 T \ln 20/T. \quad (2)$$

The total increase in entropy below 0.015°K over a linear extrapolation is $0.0075 nR$, and the total estimated entropy below 0.2°K is $\sim 0.46 nR$, in fair agreement with higher-temperature thermodynamic data [3].

References

1. L.D. LANDAU, *Sov. Phys. J.E.T.P.* 3, 920 (1965); 5, 101 (1957).
2. W.R. ABEL, A.C. ANDERSON, W.C. BLACK and J.C. WHEATLEY, *Physics* (1965).
3. B.M. ABRAHAM, D.W. OSBORNE and B. WEINSTOCK, *Phys. Rev.* 98, 551 (1955).
4. A.C. ANDERSON, W. REESE and J.C. WHEATLEY, *Phys. Rev.* 130, 495 (1963).
5. M. STRONGIN, G.O. ZIMMERMAN and H.A. FAIRBANK, *Phys. Rev.* 128, 1983 (1962).
6. D.F. BREWER and J.R.G. KEYSTON, *Nature, Lond.* 191, 1261 (1961).

Publishers Note

We regret that this paper was inadvertently omitted from Vol. 1, No. 6 where it should have followed immediately after *Thermal and magnetic properties of liquid He^3 at low pressure and at very low temperatures* by W. R. ABEL, A. C. ANDERSON, W. C. BLACK and J. C. WHEATLEY.