the neighboring He^3 appear necessary. If these functions assume the form anticipated in Sec. II, then significant relaxation about the He^4 will not be necessary. To get J near the observed value an improved form for the correlation function $f(r_{ij})$ is also needed, and this represents a difficult task. One of the chief difficulties is that those parts of $|O\rangle$ which are important to J have little influence on E_0 and so are not well determined by an energy variational method.

Simply evaluating the change in the self-consistent harmonic force constants around the He^4 does not explain the large observed τ_{pt}^{-1} suggesting that this model is too restrictive. On the other hand, although τ_{pt}^{-1} can be predicted directly using a continuum model, this model is so crude that it tells us little in detail about the defect.[14] It does suggest, however, that division of defect properties into mass and force constant changes may be artificial and that large relaxation around the He^4 is not necessarily needed to explain τ_{pt}^{-1}.

ACKNOWLEDGMENTS

The author gratefully acknowledges particularly valuable discussion of this subject with Professor L. H. Nosanow and Dr. M. G. Richards.

[1] M. G. Richards, J. Hatton, and R. P. Giffard, Phys. Rev. 139, 91 (1965); R. P. Giffard and J. Hatton, Phys. Rev. Letters 18, 1106 (1967).

[2] B. Bertman, H. A. Fairbank, R. A. Guyer, and C. W. White, Phys. Rev. 142, 79 (1966).

[3] Bal Krishna Agrawal, Phys. Rev. 162, 731 (1967).

[4] J. Callaway, Phys. Rev. 113, 1046 (1959).

[5] Lord Rayleigh, Theory of Sound (MacMillan and Co., London, 1896), Vol. II, p. 149.

[6] P. G. Klemens, Proc. Phys. Soc. (London) A68, 1113 (1955).

[7] P. G. Klemens and A. A. Maradudin, Phys. Rev. 123, 804 (1961).

[8] L. H. Nosanow, Phys. Rev. 146, 120 (1966).

[9] T. R. Koehler, Phys. Rev. Letters 18, 654 (1967).

[10] L. H. Nosanow and W. J. Mullin, Phys. Rev. Letters 14, 133 (1965). [Also the $T=0°K$ limit in L. H. Nosanow and C. M. Varma, Phys. Rev. Letters 20, 912 (1968)].

[11] J. H. Hetherington, W. J. Mullin, and L. H. Nosanow, Phys. Rev. 154, 175 (1967).

[12] R. E. Peierls, Quantum Theory of Solids (Oxford-Clarendon Press, Oxford, England, 1955), p. 121.

[13] J. H. Vignos and H. A. Fairbank, Proceedings of the Eighth International Conference on Low-Temperature Physics, London, 1962, edited by R. O. Davies (Butterworths Scientific Publications Ltd., London, 1962).

[14] The model is reasonable in this case as $T \lesssim \theta/10$ and long wave phonons are unaffected by changes in detail.

PHYSICAL REVIEW VOLUME 177, NUMBER 1 5 JANUARY 1969

Experimental Heat Capacity of Pure Liquid He^3†

A. C. Mota,* R. P. Platzeck, R. Rapp,* and J. C. Wheatley*

Centro Atômico Bariloche, Comisión Nacional de Energía Atómica
S. C. de Bariloche (R. N.), Argentina

(Received 17 July 1968)

Measurements of the heat capacity of pure He^3 at 0.24 atm obtained by a differencing method are presented for the temperature range from 20–150 m°K. The temperature scale T^* used is that valid for powdered cerium magnesium nitrate in the form of a right circular cylinder with diameter equal to height. There is excellent agreement between the present and earlier measurements. Considering all low-pressure difference data we find that from 6–125 m°K the ratio of heat capacity to magnetic temperature decreases linearly with increasing temperature. The relationship of the measurements to the temperature scale and to theories of spin fluctuations in He^3 is also discussed.

I. INTRODUCTION

In recent years the heat capacity of pure He^3 has been of considerable interest. It is related to the Landau theory of Fermi liquids.[1] It bears directly on the question of superfluidity in He^3.[2,3] What is known of its temperature dependence was not predicted by theory and has been the subject of theoretical speculation.[4,5] Owing to the possibility of a superfluid transition, most recent measurements have emphasized the properties of He^3 at the lowest achievable temperatures.[3,6] As a result, in no single experiment have accurate measurements been made in the temperature range, 20–150 m°K, of the present work. Recently Doniach and Engelsberg[7] devised a qualitatively successful theory to explain the heat capacity of pure He^3. In their theory, liquid He^3 is conceived as a nearly ferromagnetic Fermi fluid in which spin fluctuations play a major role. Following this idea through, Rice[8] worked out a theory of transport in He^3 which predicted remarkably well the results of thermal conductivity measurements.[9–11] The importance of spin fluctuations in understanding the heat capacity of He^3 has been given further emphasis by calculations of Brenig and co-workers[12] and of Amit, Kane, and Wagner,[13] though it has not been universally accepted.[14] One characteristic of the above theories is that they predict not only the limiting low-temperature behavior of He^3, as in the Landau theory, but also the finite temperature properties. In particular they predict that

$$C/n_3RT=\gamma+\Gamma T^2\ln(T/\theta_c)+\cdots , \qquad (1)$$

where C is the heat capacity, n_3 is the number of moles of He^3, R is the gas constant, T is the absolute temperature, γ and Γ are constants, and θ_C is a characteristic temperature. According to recent work of Brinkman and Engelsberg,[15] however, the limiting temperature dependence of Eq. (1) should not be achieved except at temperatures below a few millidegrees. They suggest that in the present temperature range many terms must be considered in the series development of C/nRT.

With the exception of the results of Ref. 6, which are based on a nuclear magnetic resonance temperature scale in copper and are of relatively poor precision, all very low temperature measurements of the heat capacity of He^3 have been made on a magnetic temperature scale T^* valid for powdered cerium magnesium nitrate (CMN) in the form of a right circular cylinder with diameter equal to height. This magnetic temperature scale was interpreted by one of us[16] in terms of properties of Fermi liquids with the conclusion that T^*, subject to a correction estimated to be less than a few tenths of a millidegree, is the same as the Kelvin temperature T down to about 3m°K. This interpretation was called in question recently by Abraham and Eckstein[17] who based their analysis on an assumed T^{-2} dependence[18] of the heat capacity of CMN between 6 and 15 m°K. They concluded that the above powder thermometer temperature T^* should be corrected upward by 1.7 m°K to obtain the magnetic temperature T_S^* indicated by a spherical single crystal. According to Ref. 18 the temperature T_S^* is the same as the Kelvin temperature above 6 m°K. Abraham and Eckstein's proposed correction to the powder temperature scale has a profound effect on the interpretation of the experiments in terms of the Fermi-liquid theory. This effect has not yet been discussed quantitatively. Such a discussion will be undertaken in this paper since there seems to be some question[20] whether the experimental precision of the He^3 heat-capacity measurements is high enough to demonstrate that in fact Abraham and Eckstein's correction does lead to any real difficulties.

Recent direct measurements of Abel and Wheatley[19] intercomparing the magnetic temperatures indicated by a powder and a single-crystal sphere do not support Abraham and Eckstein's conclusions but do favor the original interpretation.[16] However, Abel and Wheatley find that, as one might expect, the shape correction for a powder thermometer is not precisely the same for all such thermometers but in fact varies by an amount probably of order 0.1–0.2 m°K. In the present work we shall therefore use the uncorrected T^* scale with the word of caution that the Kelvin temperature differs from T^* by a rather uncertain amount which is estimated to be a few tenths of a millidegree. This uncertain correction will not have a large effect on the interpretation of the present results, whose lower temperature limit is 20 m°K.

Measurements of the heat capacity of liquid He^3 are reviewed in Ref. 3. In no single experiment were sufficiently accurate measurements obtained over a wide enough temperature range to allow quantitative comparison with the new theoretical work. Systematic errors in the measurement of T and n_3, Eq. (1), inhibit the quantitative comparison of different sets of data. Moreover the lowest-temperature results of Anderson, Reese, and Wheatley,[21] for example, were marred by the defect that the calorimeter "background" heat capacity was not known. This defect was rectified in the work described in Ref. 3 by using a "difference" method described in Sec. II to eliminate the background heat capacity. However, in the work reported there the heat capacity at low pressure was measured only to 50 m°K.

In the present experiments we have measured the heat capacity of pure He^3 (less than 10 ppm He^4) at a pressure of 0.24 atm over a temperature range from 20–150 m°K. These measurements are important not only as they determine the temperature dependence of the heat capacity of pure He^3 but also as they relate to the confidence which may be placed in the earlier measurements[3] which extend to lower temperatures.

II. EXPERIMENTAL

Both our general experimental method and our methods of data analysis are very similar to those described in Ref. 3, to which the reader is referred for a detailed discussion of these matters. The He^3 was contained in an epoxy cell in intimate contact with a magnetic thermometer of powdered cerium magnesium nitrate in the form of a right circular cylinder with diameter equal to height and of mass 1.042 g. Heat was added electrically. Susceptibilities were measured by means of a 17-Hz mutual inductance bridge. In the first series of measurements the heat-capacity cell contained 0.0183 moles of He^3. The cell was then modified without changing the thermometer in any way to increase the volume available for He^3. The modified cell contained 0.0344 moles of He^3. Measurements of heat capacity were then repeated. Above 30 m°K the cell background heat capacity was negligible.

Aside from its advantage of eliminating the calorimeter "background" heat capacity the differencing method which we use has other advantages. Each new experiment requires a new calibration of the magnetic thermometer and a new measurement of the number of moles of He^3 in the cell. Hence errors in these quantities are readily detected as systematic inconsistencies in the values of $(C_1 - C_2)/(n_1 - n_2)RT^*$, C_1/n_1RT^*, and C_2/n_2RT^* at higher temperatures where the "background" heat capacity is negligible compared with that of the He^3.

III. RESULTS AND DISCUSSION

The results of our measurements at 0.24 atm with C/nRT^* plotted linearly against T^* are shown by closed circles in Fig. 1. Also shown are both the results of Ref. 3 for pure He^3 at 0.28 atm (open circles) and at 27.0 atm (open squares), and the results[22,23] for a 5.0% solution of He^3 in superfluid He^4 (closed squares). Even without numerical analysis it is clear that there is excellent agreement between the present measurements and those of Ref. 3 in the temperature region from 20–50 m°K where the two sets of data overlap. This increases our confidence in both measurements. It is also clear that within the experimental scatter the quantity C/nRT^* depends linearly on T^* from the lowest temperatures to 125 m°K. This temperature dependence was suggested in Ref. 21, but both experimental imprecision and ignorance of the calorimeter "background" heat capacity prevented a strong case from being made. Owing either to experimental imprecision or to inaccuracy resulting from ignorance of the $T^* - T$ correction it is quite possible that C/nRT really should be described by some other temperature dependence below approximately 20 m°K.

We have used the method of least squares to treat the data on low-pressure He^3 in Fig. 1. Since there appears to be some upward curvature at the highest temperatures we have used only data below 125 m°K to make the straight-line fits described below. Data were fitted to

$$C/nRT^* = \gamma - \beta T^* . \quad (2)$$

We considered four sets of data: (1) present results between 50 and 125 m°K; (2) all present results below 125 m°K; (3) all results of Ref. 3 at 0.28 atm; and (4) all present results below 125 m°K and all results of Ref. 3 at 0.28 atm. All points are equally weighted. The results of these analyses are given in Table I. The errors indicated are the standard deviations. The present experimental results are remarkably consistent with the 0.28-atm results of Ref. 3. There seems to be little reason not to combine the two sets of data. The values of γ given in Table I correspond to $m^*/m = 3.03$, which probably is an upper limit. For the purpose of allowing other interpretations of our data we list them explicitly in Table II. The data of Ref. 3 are listed in Table I of that paper. Above 10m°K the 27.0-atm data of Ref. 3 also are an excellent fit to a linear relationship between C/nRT^* and T^*. A least-squares fit to the experimental data for $T^* > 10$ m°K is

$$C/nRT^* = (4.63 \pm 0.01)(K°)^{-1} - (22.5 \pm 1.1)T^*(K°)^{-2}, \quad (27.0 \text{ atm}).$$

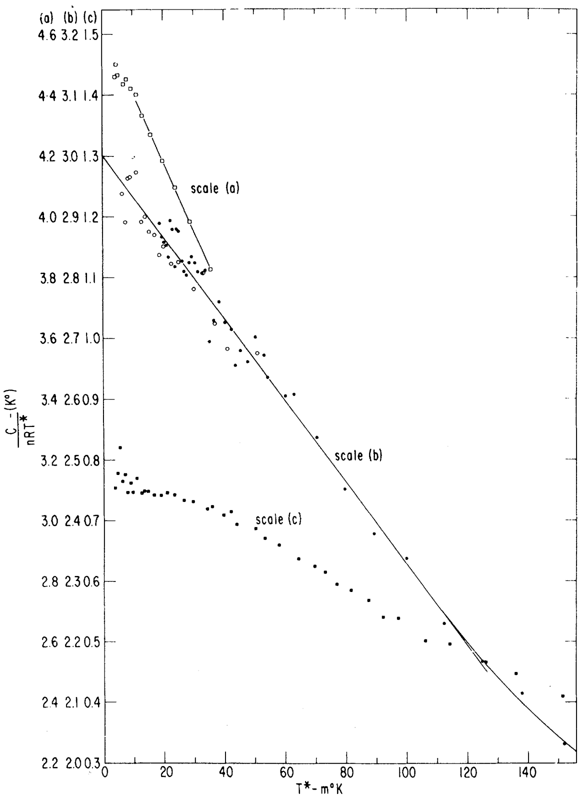

FIG. 1. Ratio of normalized specific heat C/nR to magnetic temperature T^* of pure He^3 at 0.24 atm (●●●) from the present work, of pure He^3 at 0.28 atm (○○○) from Ref. 3, of pure He^3 at 27.0 atm (□□□) from Ref. 3, and of a 5% solution of He^3 in superfluid He^4 (■■■) from Refs. 22 and 23.

TABLE I. Least-squares determined parameters for Eq. (2).

Experimental data processed	No. of points	Temperature range (m°K)	γ $(K°)^{-1}$	β $(K°)^{-2}$
Present experiment: 0.24 atm	11	50–125	3.04 ± 0.02	7.2 ± 0.2
Present experiment: 0.24 atm	38	19–125	3.01 ± 0.01	6.9 ± 0.2
Reference 3: 0.28 atm	40	6–51	3.00 ± 0.01	7.1 ± 0.6
Present experiment: 0.24 atm and Reference 3: 0.28 atm	78	6–125	3.00 ± 0.01	6.74 ± 0.15

TABLE II. C/nR and C/nRT^* for pure He^3 at 0.24 atm.

T^* (m°K)	$10^2 C/nR$	C/nRT^* [(K°)$^{-1}$]
18.93	5.47	2.888
19.62	5.62	2.866
20.27	5.79	2.858
21.03	6.00	2.853
21.71	6.15	2.833
22.40	6.48	2.894
23.09	6.65	2.879
23.80	6.70	2.817
24.48	7.05	2.880
25.13	7.23	2.876
26.11	7.38	2.826
26.80	7.53	2.809
27.64	7.75	2.803
28.39	8.02	2.824
29.32	8.31	2.834
30.25	8.54	2.824
31.37	8.81	2.809
32.71	9.18	2.806
33.82	9.51	2.811
35.07	9.45	2.694
36.55	9.97	2.729
38.35	10.58	2.759
40.20	10.96	2.725
42.28	11.48	2.714
43.56	11.57	2.655
45.29	12.13	2.679
47.74	12.70	2.660
50.20	13.56	2.702
53.06	14.17	2.671
56.24	14.82	2.635
60.13	15.66	2.605
63.54	16.57	2.607
70.28	17.82	2.536
79.53	19.49	2.450
89.14	21.19	2.377
99.89	23.34	2.337
112.2	25.01	2.229
124.8	27.05	2.167
138.0	29.17	2.114
152.0	30.88	2.031

It is also possible to fit the experimental data to a relation of the form of Eq. (1). In this case there are three parameters to fit: γ, Γ, and θ_C. These are obtained by obtaining the best straight-line fit to

$$(\gamma - C/nRT^*)/T^{*2} = \Gamma \ln(T/\theta_C).$$

Such a fit is demonstrated in Fig. 2 and corresponds to

$$\gamma = 2.93(\text{K}°)^{-1}, \quad \Gamma = 57.4(\text{K}°)^{-3}, \quad \theta_C = 0.29_3\,°\text{K}.$$

The low-temperature scatter is extremely sensitive to γ. Even for the best fit the scatter below 50 m°K is so large as to make impossible any meaningful comparison with Eq. (1). Between 50 and 150 m°K the data are reasonably represented by Eq. (1). There appears to be no compelling reason, particularly considering the arguments of Brinkman and Engelsberg,[15] to prefer Eq. (1) over

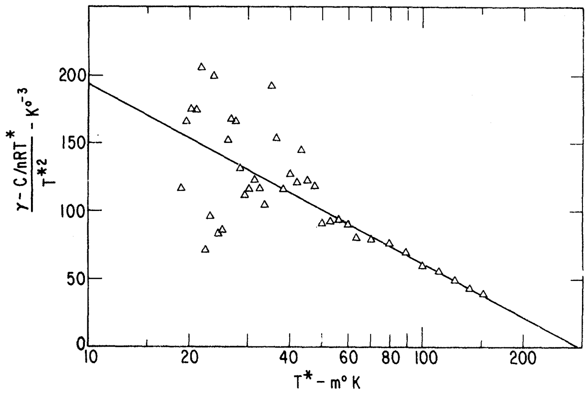

FIG. 2. Fit of the present specific heat data to the temperature dependence of Eq. (1) in the text.

Eq. (2) in the present temperature region. Nevertheless, it is interesting to compare the characteristic temperature $\theta_C = 0.29$°K derived from the heat-capacity data with the characteristic temperature θ_K which may be derived from thermal conductivity data. Using the most probable corrections to the temperature scale, Abel and Wheatley[19] reworked the thermal conductivity data.[9] From their results and the numbers worked out in Ref. 10 we find

$$\theta_K = (0.68 \pm 0.12)°\text{K}.$$

Following Doniach and Rice θ_K and θ_C should be related by $\theta_K/\theta_C = \overline{Q}$, where $\overline{Q}$ is a dimensionless number equal[10] to 1.24 for low-pressure He^3. There is not quantitative agreement.

At higher temperatures the present measurements overlap those of a number of other workers. At 125 m°K we find $C/nR = 0.270$. Estimating graphically, we find that at this temperature Abraham *et al.*[25] measured $C/nR = 0.273$; Anderson, Reese, and Wheatley[21] measured 0.256; Brewer, Daunt, and Sreedhar[26] measured 0.247; and Strongin, Zimmermann, and Fairbank[27] measured 0.249. Our results are thus on the high side of the scatter, though rather close to those of Ref. 25. They are 5% different from those of Ref. 21 and hence within the estimated error of that experiment.

We now wish to turn our attention to the effect on the heat-capacity results represented in Fig. 1 of a correction to the temperature scale based on the arguments given by Abraham and Eckstein.[17] These authors start with the assertion, which they assumed had been proved quantitatively by Hudson and Kaeser,[18] that the heat capacity of CMN obeys the T^{-2} law (T is Kelvin temperature) above 6 m°K. Actually Hudson and Kaeser claimed the T^{-2} law to be valid only between 6 and 15 m°K. According to Ref. 18 above $T = 6$ m°K the magnetic temperature $T_S^{*(SC)}$ indicated by a single crystal sphere is the same as T. Abraham and Eckstein recognize that since the powder thermometers do not have a spherical shape there should be some correction Δ such that

$$T_S^{*(P)} = T^* + \Delta, \qquad (3)$$

where $T_S{}^{*(P)}$ is the magnetic temperature indicated by a powder having a spherical shape. They assume that $T_S{}^{*(P)}$ is the same as $T_S{}^{*(SC)}$. This is probably a good assumption at sufficiently high temperatures though it is not at the lowest temperatures.[19] The quantity Δ can be evaluated empirically by plotting $(C_{\mathrm{CMN}}/n_{\mathrm{CMN}}R)^{-1/2}$ versus T^*. A straight line should be found with Δ as intercept.

In order to make the above analysis we need C_{CMN} versus T^*. The difference measurements made in Ref. 3 were needed to eliminate the calorimeter "background" heat capacity, which is probably almost entirely that of the CMN thermometer. If we *assume* that the "background" heat capacity is that of the CMN, then we can proceed with the analysis. It is important to recognize that in the actual measurements one measures the sum of CMN and He^3 heat capacity, the differencing method allowing the individual parts to be determined. Above $T^* = 6$ m°K the majority of the heat capacity was in the He^3, so C_3 can be expected to have greater precision than C_{CMN}. This is important to keep in mind when considering the credibility of the He^3 data with respect to those for the CMN. A final point is that in Ref. 3 care was taken not to refer to the background heat capacity as the CMN heat capacity since it could not be assumed that there were no other appreciable sources of heat capacity. The recent results of Ref. 17 for the CMN heat capacity are sufficiently similar to those of Ref. 3 to make reasonable the assumption that it was indeed C_{CMN} measured in Ref. 3.

In Fig. 3 we plot $(C_{\mathrm{CMN}}/n_{\mathrm{CMN}}R)^{-1/2}$ versus T^* with data taken from Ref. 3. The straight line shown was fitted by the method of least squares with equal point weighting using data for $T^* > 6$ m°K. We find

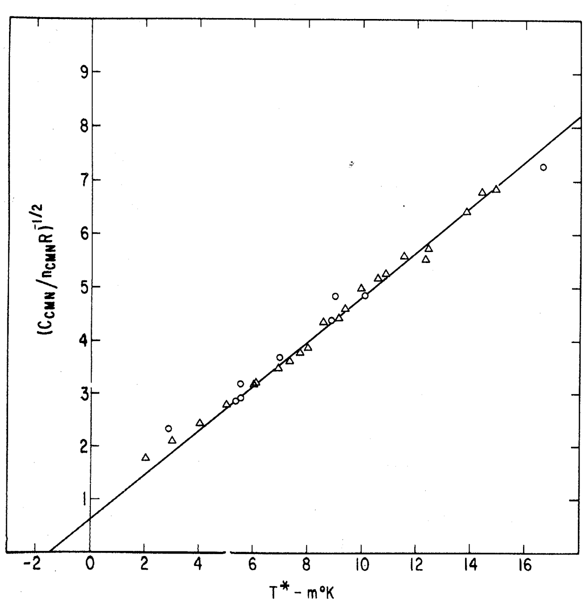

FIG. 3. Plot of $C_{\mathrm{CMN}}/n_{\mathrm{CMN}}R)^{-1/2}$ for the data of Ref 3. ($\Delta\,\Delta\,\Delta$) and of Ref. 17 (○○○). Assuming a T^{-2} law for the normalized specific heat, this plot can be used to determine Δ (see text).

$$\Delta = +(1.48 \pm 0.24)\ \mathrm{m°K}$$

and

$$C_{\mathrm{CMN}}(T^* + \Delta)^2/n_{\mathrm{CMN}}R = (5.67 \pm 0.14)\ (\mathrm{m°K})^2.$$

Inspection of the figure shows that if magnetic temperatures lower than 6 m°K are accepted in making the least-squares fit, then the derived value of Δ will increase. If data are used to 5 m°K, the mean value of Δ increases from 1.48 to 1.54 m°K. The value of

$$C_{\mathrm{CMN}}(T^* + \Delta)^2/n_{\mathrm{CMN}}R$$

is essentially the same as that, 5.76 $(\mathrm{m°K})^2$, given in Ref. 18. Whether or not this agreement is coincidental or is a clue to the source of the discrepancy is not known. We also show in Fig. 3 the data of Abraham and Eckstein[17] for CMN heat capacity. Their results are rather similar to ours, though when fitted by least squares using data from 5.3 to 16.6 m°K they yield

$$\Delta = +(2.5 \pm 0.5)\ \mathrm{m°K}$$

and

$$C_{\mathrm{CMN}}(T^* + \Delta)^2/n_{\mathrm{CMN}}R = (6.7 \pm 0.3)\ (\mathrm{m°K})^2.$$

The CMN heat capacity data treated to obtain $\Delta = 1.48$ m°K were obtained simultaneously with the pure He^3 data of Fig. 1 at 0.28 and 27.0 atm. Moreover the results for the heat capacity of a 5% solution of He^3 in He^4 plotted in Fig. 1 were obtained[22] by subtracting from a total measured heat capacity that of CMN as measured in Ref. 3, appropriately adjusted for the actual mass of CMN. Hence a consistent analysis of these data using Abraham and Eckstein's suggestions would adjust T^* upward by 1.48 m°K to find T. We have therefore replotted in Fig. 4 the data shown on

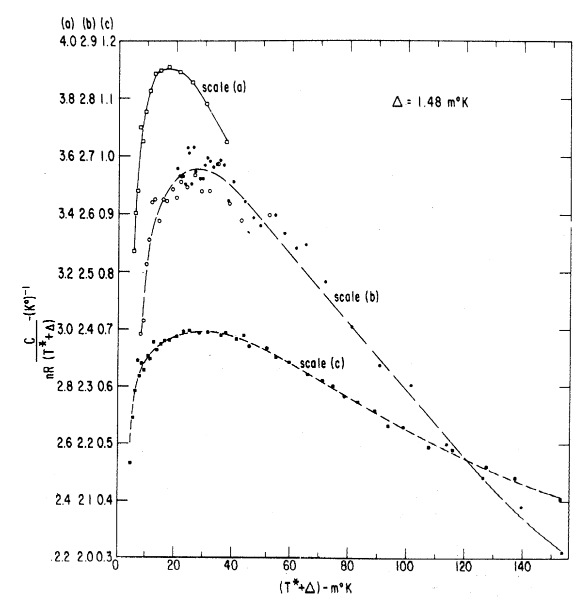

FIG. 4. Replot of the data shown in Fig. 1 after making the substitution of $T^* + \Delta$ for T^*, with $\Delta = 1.48$ m°K as derived from the results shown on Fig. 3.

Fig. 1 using this correction. Relative to the precision of the measurements it is clear that such a correction does indeed have a profound effect on the temperature dependence of the He^3 heat capacity, both pure He^3 and the dilute solution being affected in a qualitatively similar manner. There is a clear-cut discrepancy. Either pure He^3 and dilute solutions have characteristics which are not predicted by theories of the Fermi liquid or the heat capacity of CMN does not obey quantitatively the T^{-2} law in the range 6–15 m°K. The direct magnetic thermometry experiments of Abel and Wheatley[19] suggest that in powder thermometers Δ is only a few tenths of a millidegree. Hence one concludes that in fact

$$C_{\mathrm{CMN}}(T^* + \Delta)^2/n_{\mathrm{CMN}}R$$

is not constant, but increases with temperature in the range of measurement.

IV. CONCLUSIONS

The ratio C/nRT^* for pure He^3 at low pressure, where T^* is the magnetic temperature indicated by a powder thermometer, decreases linearly with T^* from 6–125 m°K within an rms experimental scatter of about ± 1%. A similar linear dependence between 10 and 35 m°K is found for pure He^3 at 27.0 atm. Above 50 m°K the data also fit a law

$$C/nRT = \gamma + \Gamma \ln T/\theta\,.$$

The above results are affected by corrections to T^* needed to convert it to Kelvin temperature. It is demonstrated that such a correction, based on the assumptions of Ref. 17 but unwarranted according to the direct measurements of Ref. 19, qualitatively affects the temperature dependence of the heat capacity of both pure He^3 and a 5% dilute solution. The actual dependence of C/nRT on T, where T is Kelvin temperature, below 20 m°K will depend on the magnitude of the adjustment of T^* to obtain T. These corrections are expected to be no more than a few tenths of a millidegree down to about 3 m°K.[16,28]

---

†This work has been supported by the Comisión Nacional de Energía Atómica of the Republic of Argentina, by the U. S. National Science Foundation under Grants Nos. NSF-GP329 and NSF-GP3586, and by the Consejo Nacional de Investigaciones Científicas y Técnicas of the Republic of Argentina. Part of the analysis was supported by the U. S. Atomic Energy Commission under Contract No. AT (11-1)-34, P. A. 143.

*Now at Department of Physics, University of California at San Diego, La Jolla, California.

[1]L. D. Landau, Zh. Eksperim. i Teor. Fiz. 30, 1058 (1956) [English transl.: Soviet Phys. – JETP 3, 920 (1957)].

[2]V. P. Peshkov, Zh. Eksperim. i Teor. Fiz. 48, 997 (1965) [English transl.: Soviet Phys. – JETP 21, 663 (1965)].

[3]W. R. Abel, A. C. Anderson, W. C. Black, and J. C. Wheatley, Phys. Rev. 147, 111 (1966).

[4]P. W. Anderson, Physics 2, 1 (1965).

[5]R. Balian and D. R. Fredkin, Phys. Rev. Letters 15, 480 (1965).

[6]E. B. Osgood and J. M. Goodkind, Phys. Rev. Letters 18, 894 (1967).

[7]S. Doniach and S. Engelsberg, Phys. Rev. Letters 17, 750 (1966).

[8]M. J. Rice, Phys. Rev. 159, 153 (1967).

[9]W. R. Abel, R. T. Johnson, J. C. Wheatley, and W. Zimmermann, Phys. Rev. Letters 18, 737 (1967).

[10]J. C. Wheatley, Phys. Rev. 165, 304 (1968).

[11]A. C. Anderson, J. I. Connolly, O. E. Vilches, and J. C. Wheatley, Phys. Rev. 147, 86 (1966).

[12]W. Brenig and H. J. Mikeska, Phys. Letters 24A, 332 (1967); W. Brenig, H. J. Mikeska, and E. Riedel, Z. Physik 206, 439 (1967); E. Riedel, Z. Physik 210, 403 (1968).

[13]D. J. Amit, J. W. Kane, and H. Wagner, Phys. Rev. Letters 19, 425 (1967).

[14]S. Misawa, Progr. Theoret. Phys. (Kyoto) 38, 1207 (1967).

[15]W. F. Brinkman and S. Engelsberg, Phys. Rev. 169, 417 (1968).

[16]J. C. Wheatley, Ann. Acad. Sci. Fennicae Ser. A VI, No. 210, 15 (1966).

[17]B. M. Abraham and Y. Eckstein, Phys. Rev. Letters 20, 649 (1968).

[18]R. P. Hudson and R. S. Kaeser, Physics 3, 95 (1967).

[19]W. R. Abel and J. C. Wheatley, Phys. Rev. Letters 21, 597 (1968).

[20]R. P. Hudson, private communication to J. C. Wheatley.

[21]A. C. Anderson, W. Reese, and J. C. Wheatley, Phys. Rev. 130, 495 (1963).

[22]W. R. Roach, Ph. D. thesis, University of Illinois, 1966 (unpublished).

[23]A. C. Anderson, D. O. Edwards, W. R. Roach, R. E. Sarwinski, and J. C. Wheatley, Phys. Rev. Letters 17, 367 (1966).

[24]S. Doniach and M. J. Rice, Contribution to the Conference on Theoretical Physics, Birmingham, England, July, 1967 (unpublished).

[25]B. M. Abraham, M. Durieux, C. J. N. van den Meijdenberg, and D. W. Osborne in Proceedings of the Ninth International Conference on Low Temperature Physics, edited by J. G. Daunt, D. O. Edwards, F. J. Milford, and M. Yaqub (Plenum Press, New York, 1965), Pt. A, p. 133.

[26]D. F. Brewer, J. G. Daunt, and A. K. Sreedhar, Phys. Rev. 115, 836 (1959).

[27]M. Strongin, G. O. Zimmermann, and H. A. Fairbank, Phys. Rev. 128, 1983 (1962).

[28]W. C. Black, Ph. D. thesis, University of Illinois, 1967 (unpublished).