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Authors

Mayberry, M.C.
Phillips, N.E.

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SPECIFIC HEAT OF ^3He IN THE FERMI LIQUID REGION

M. C. Mayberry, William E. Fogle* and Norman E. Phillips
Department of Chemistry, and Materials and Molecular Research
Division, Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720

ABSTRACT

A CMN thermometer has been calibrated by nuclear orientation thermometry at low temperatures and by He vapor pressure thermometry at high temperatures. The calibration agrees well with the NBS temperature scale between 100 and 200 mK. Specific heat data on ^3He in the Fermi liquid region obtained with this thermometer are in good agreement with recent measurements at Bell Laboratories. It is argued that discrepancies with other data arise from differences in the underlying temperature scales.

INTRODUCTION

The effective mass for ^3He that can be derived from the specific heat in the normal or Fermi liquid region is of fundamental importance to an understanding of the superfluid states as well as the normal state. Its value, however, is not well established because the existing specific heat data vary by up to 40% in magnitude (see Table I for examples) and also exhibit significantly different temperature dependences. The pioneering investigation of the Fermi liquid properties by Wheatley and colleagues produced extensive specific heat data¹ (hereinafter referred to as the La Jolla data although the measurements were actually made at several different laboratories) which were generally accepted as fairly close to correct. More recent measurements at Helsinki² gave substantially lower values for the specific heat and a different temperature dependence. Both sets of data have been approximately verified by independent measurements at other laboratories: in the case of the La Jolla data by Hebral et al.³ (Grenoble) in measurements near the melting pressure; in the case of the Helsinki data by Zeise et al.⁴ (Cornell-I) in measurements at pressures throughout the liquid range. Furthermore, Greywall⁵ (Bell Laboratories) has reported intermediate values of the specific heat that agree with data obtained by Halperin et al.⁶ (Cornell-II) near the melting pressure.

The disparities in the specific heat data have led to speculation that surface contributions to the specific heat, which might be different in the different experimental arrangements, are significant. On the other hand, the values for the ratio of the heat capacity just below the superfluid transition to that just above the transition and for the ratios of the heat capacities at different pressures are much more consistent with one another (see Table II). This suggests certain types of systematic errors, the most probable

*Present address: National Bureau of Standards,
Washington D.C. 20234

TABLE I. Heat capacity of liquid ^3He at 10 mK, 0 and 28 atm pressure, as reported from five laboratories.

Laboratory	Zero Pressure		28 atm	
	$\frac{C}{RT} \text{ (K}^{-1}\text{)}$	Deviation from mean	$\frac{C}{RT} \text{ (K}^{-1}\text{)}$	Deviation from mean
La Jolla ^a	2.94	+18%	4.41	+11%
Grenoble ^b	—	—	4.70	+18%
Helsinki ^c	2.11	-16%	3.33	-16%
Cornell-I ^d	2.20	-12%	3.30	-17%
Bell Laboratories ^e	2.74	+10%	4.11	+ 3%
Cornell-II ^f	—	—	4.00	+ 1%

^aReference 1^dReference 4^bReference 3^eReference 5^cReference 2^fReference 6

TABLE II. Heat capacity ratios for liquid ^3He , as reported from four laboratories. C_A and C_N are the specific heats in the superfluid A and normal phases, respectively, and T_A is the equilibrium temperature.

Laboratory	$\left \frac{C(28 \text{ atm})}{C(0 \text{ atm})} \right _{10 \text{ mK}}$		$\left \frac{C_A}{C_N} \right _{T_A, 33 \text{ atm}}$	
	Value of ratio	Deviation from mean	Value of ratio	Deviation from mean
La Jolla ^a	1.50	-1.7%	2.85	-4.0%
Cornell-II ^b	—	—	3.00	+1.0%
Helsinki ^c	1.58	+3.5%	3.06	+3.0%
Bell Laboratories ^d	1.50	-1.7%	—	—

^aReferences 1 and 7^cReference 2^bReference 6^dReference 5

of which is temperature scale error. Furthermore, while there is no obvious correlation between the reported specific heat and the surface area of CMN or sinter, there is a correlation between specific heat and temperature scale: the Grenoble and La Jolla measurements

were based on a Curie-Weiss relation,

$$\chi = \frac{C}{T - \Delta}, \quad (1)$$

for a CMN thermometer with $\Delta = 0$; the Cornell-I data were based on a temperature scale derived from the Helsinki phase diagram; the Bell Laboratories temperature scale is anchored to the same thermodynamic temperature measurements that are the basis of the Cornell-II data. These considerations suggest the importance of additional measurements on temperature scales that can be independently related to the thermodynamic scale. New measurements of this type are reported here and, in addition, the earlier data are re-examined from the point of view of the possibility that the discrepancies arise primarily from temperature scale differences.

MEASUREMENTS

With one exception (Cornell-II) the temperature scales used in the specific heat measurements described above depend on the use of Eq. (1) for the susceptibility of a cylinder, with diameter equal to height, of powdered CMN or LCMN (La-diluted CMN). These scales are generally tied to the He vapor pressure scales at high temperatures, but an independent low-temperature determination of T is required to obtain the value of Δ , which is assumed to be a constant and is of the order of 0 ± 1 mK. The scale used in our measurements was of this type with CMN as the working substance and Δ determined by $\text{Co}^{60}\text{Co NO}$ (nuclear orientation) thermometry. Independent NO temperatures were derived from both "on-axis" and "off-axis" γ -ray intensities. Fifteen comparisons at about 17 mK gave an average difference of 0.11% with a standard deviation of 0.77%. Temperatures obtained with a $\text{Co}^{60}\text{Co NO}$ thermometer have been tested, to comparable accuracy, by comparison with a noise thermometer at NBS.⁸ The agreement between the on-axis and off-axis temperatures indicates the absence of certain possible experimental errors that would arise from misalignment, closure domains etc. A total of five different CMN thermometers using either grease or ^3He to provide thermal contact and either ac or dc measuring techniques were investigated. In all but one of these the CMN was from a sample that had been used for thermodynamic measurements that gave $\Delta=0.75$ mK for a spherical single crystal,⁹ and the values of Δ for the powdered samples were 0.95 mK (to within a variation of about 0.1 mK apparently associated with effects of different superconducting coils and flux-trapping or shielding tubes). One of these thermometers was used in the specific heat measurements. (For the one CMN thermometer that used CMN from a different source, apparently with excess water of hydration, $\Delta \approx 0$ mK). The temperature scale has been compared¹⁰ with an NBS SRM 768 fixed point device¹¹. At the Ir, AuAl_2 , and AuIn_2 points (~ 99 –200 mK) discrepancies with the NBS scale are 0.35% or less, and at the Be point (~ 23 mK) 1.3%, which is reasonable given the 1.7% transition width. At the W point (~ 16 mK) the scale is 1.1 mK higher than suggested by the original NBS calibration and 0.6 mK

higher than the revised value. However, our value of the W point (16.26 mK) is in better agreement with the Helsinki values¹² (15.86, 16.29 mK) determined by Pt NMR thermometry, and with the Bell Laboratories value¹³ (15.97 mK) determined relative to the Cornell-II thermodynamic scale⁶. If, as now seems to be the case, the W points have the same value for all the fixed point devices, these comparisons are particularly relevant to the specific heat data.

The specific heat data taken to date were obtained in a cell that was designed primarily for thermometer intercomparisons and did not permit measurements at pressures above the vapor pressure. The working thermometer, the CMN thermometer already described, contained approximately 0.1 cm^3 of CMN that passed a 37μ sieve and was immersed in the ^3He sample. Thermal contact to the Cu cell body was made through sintered Cu powder. It was possible to fill the cell to various levels above the sinter (with 5 to 15 cm^3 of liquid ^3He) and thus to determine separately the heat capacity of the cell, with ^3He filling the sinter, and that of liquid above the sinter. As expected for such an arrangement, the thermal equilibrium times were long, but good thermal isolation made it possible to establish linear temperature drifts between successive heat capacity points. There is thus no reason to expect errors from this source greater than those indicated by the precision of the data. The data are also provisional in that they cover a relatively limited temperature interval, but they do permit a choice between the values reported earlier.

Our data extend from 13 to 170 mK and are shown in Figs. 1 and 2 as C/RT where C is the molar heat capacity. Below 30 mK, C/RT is constant, as expected for a simple Fermi liquid, and approximately equal to 2.68 K^{-1} . Figures 1 and 2 also include other experimental data, represented by solid curves, for comparison. Curve (b) in Fig. 1 represents the Bell Laboratories data as reported⁵ on a modified temperature scale with Δ chosen to give a constant C/T in the low temperature limit. Above 30 mK the maximum deviation of our data from that curve is 0.5%. Below 30 mK the deviation increases to 2%, but our data are in essentially exact agreement with the Bell Laboratories data recalculated on the original temperature scale (i.e., on the scale on which the W point is 15.97 mK and Δ was chosen to correspond to the Cornell-II thermodynamic scale). Similarly, modifying our scale to give agreement with the NBS W point (rather than the NO thermometer) raises the lowest temperature points from 2% below curve (b) to 2% above. Thus, within limits imposed by uncertainties of a few percent in the temperature scales, our data agree with the Bell Laboratories data.

COMPARISON WITH OTHER DATA

Extrapolation of our data ($C/RT=2.68 \text{ K}^{-1}$) to 10 mK permits a comparison with the zero-pressure data in Table I. Assuming that all of the measurements are of the same quantity, i.e., the bulk liquid specific heat, the relatively good agreement between our data and the Bell Laboratories data, which are on independently established temperature scales, suggests that these measurements are most likely to be correct. (As noted above, the Helsinki and Cornell-I data are

Fig. 1. C/RT for liquid ^3He in the Fermi Liquid region at zero pressure. Solid curves represent reported data from La Jolla (a) and Bell Laboratories (b). Error bars indicate approximate scatter of reported data. Our data points are shown by circles.

Fig. 2. C/nRT for liquid ^3He in the Fermi Liquid region at zero pressure. Solid curves represent reported data from La Jolla (a), Bell Laboratories (b), and Helsinki (c). Error bars indicate approximate scatter of reported data. Dashed curves represent corrected data from the corresponding laboratories. Our data points are shown by circles.

on the same temperature scale). The possibility of the discrepancies with other data arising from differences in the temperature scales remain to be investigated.

In the region of the superfluid phases the phase boundaries themselves provide a convenient way to compare scales. Discrepancies between the phase diagrams reported by different laboratories have been noticed but a complete quantitative picture of the possible effect on the heat capacities is lacking. With this in mind, an analysis of the effect of temperature scales on the heat capacities was carried out using the two liquid-liquid-solid triple points, T_A and T_B , as a basis for comparison. These points provide two data points that are certainly fixed points in the thermodynamic sense and which have been widely measured. Experimental values are collected in Table III. For the purpose of comparison, a temperature scale is defined on which $T_B = 2.17$ mK and $T_A = 2.74$ mK. These temperatures were chosen to be close to the averages and to make the difference between T_B and T_A close to the average. (The Helsinki value of $T_A - T_B$, which is substantially higher than all others was omitted from this comparison). Given these defined temperatures it is possible to derive a linear function to relate a given laboratory scale T' to the comparison scale T . This function is:

$$T = \lambda T' + \tau, \quad (2)$$

with λ and τ defined by forcing T' to agree with T at T_A and T_B . Its form is justified by the prominent role of Eq. (1) in all temperature scales under consideration except that used for the Cornell-II measurements. The comparison scale which is based on somewhat arbitrary choices for T_A and T_B was originally intended only as a basis for comparison between laboratories, but the adjustment of the specific heat results that it implies substantially reduces the reported discrepancies and gives values near 10 mK that are probably correct. In the following we will therefore take the point of view that it is a reasonable approximation to the thermodynamic temperature. Given λ and τ the effect on the heat capacity can be calculated by:

$$C/RT = (C'/RT')T'/\lambda(\lambda T' + \tau), \quad (3)$$

where C/RT is the corrected value at the corrected temperature T and C'/RT' and T' are the reported values. τ corresponds to a change in the assignment of Δ for those scales based on a Curie-Weiss law. For CMN, but probably not for LCMN, it is an oversimplification to assume the τ is independent of temperature near 2 mK. However, the available data limit the analysis to a two-term fit. The major weakness of this approach is in using Eq. (2) to extrapolate temperature scale corrections derived between 2 and 3 mK to substantially higher temperatures. In Figs. 2 and 3 the corrected specific heat data are shown by the dashed curves.

The Cornell-II scale is a thermodynamic scale based on measurements of the heat of melting of ^3He and gives temperatures relative to T_A which was determined by the criterion that the entropy of the liquid is $R \ln 2$ at the minimum of the melting pressure. Using the re-

TABLE III. Experimental values of ^3He triple point temperatures.

Laboratory	T_A (mK)	T_B (mK)	$T_A - T_B$ (mK)	Type of scale
La Jolla ^a	2.725	2.155	0.570	LCMN, zero sound
Cornell-II ^b	2.75	2.18	0.57	Latent heat
Helsinki ^c	2.79	2.16	0.63	LCMN, Pt NMR
Orsay ^d	2.75	2.20	0.55	Pt NMR
Florida ^d	2.68	2.10	0.58	Latent heat
Average	2.739	2.159	0.580	

^aReference 14^bReference 6^cReference 2^dReference 15

Fig. 3 C/RT for liquid ^3He in the Fermi Liquid region at 28 atm. Solid curves represent reported data from La Jolla (a), Bell Laboratories (b), Helsinki (c) Cornell-II (d), and Grenoble (e). The Cornell-I data would be within a few percent of the Helsinki data. Error bars indicate approximate scatter of reported data. Dashed curves represent corrected data from the corresponding laboratories, except that the correction for Cornell-II is too small to be shown.

ported values of T_A and T_B gives $\lambda = 1.00$, and $\tau = -0.01$ mK. The Cornell-II specific heat data were taken along the melting pressure but have been corrected by the authors to 28 atm to give a comparison

with the La Jolla data. The pressure dependence of the heat capacity measured by the La Jolla group was assumed to be correct in making the adjustment. The use of the pressure dependence from another laboratory would change the Cornell-II values by less than 1% (see Table II). The correction to C' is less than 1% and is not shown in Fig. 3. This is the one set of data for which there is no justification for the form of Eq. (2), but the derived correction is negligible.

The Helsinki scale is based on a Pt NMR thermometer which was used to calibrate a more sensitive LCMN thermometer. From the data in Table III, $\lambda = 0.905$ and $\tau = +0.21$ mK. Although the correction was determined by the reported values of T_A and T_B alone, it expresses correctly the relation of the entire Helsinki phase diagram² to that determined recently¹⁴ at La Jolla. The correction to the specific heat, the largest of those considered, is primarily due to the large deviation of λ from one. In essence, while the measured T_A and T_B are within 1% of values determined in some other laboratories, $T_A - T_B$ is 10% higher than the average value. The ripple in the corrected data is possibly due to an error in picking the smooth curve used here to represent the reported data. The correction to the Helsinki scale eliminates the difference between the Helsinki and La Jolla phase diagrams and brings the specific heat data into much more reasonable agreement with other data, strongly suggesting that it has some validity. However, the correction is clearly inconsistent with the Helsinki determination of the W point. We have no explanation for this discrepancy. Since the Cornell-I measurements were based on the Helsinki temperature scale, the same correction applies to that data.

T_A and T_B have been determined on CMN thermometers by the La Jolla group, but not on the thermometers used in the specific heat measurements. In any case, since Δ is particularly likely to have a significant temperature dependence in this temperature interval for a CMN thermometer, it is better not to rely entirely on $T_A - T_B$ for the correction. Since the CMN thermometer used in the specific heat measurements was calibrated over a wide temperature interval it is reasonable to assume that λ is very close to 1. We have therefore assumed $\lambda = 1.00$, and estimated τ using T_A alone. Two values of T_A on CMN thermometers have been reported by the La Jolla group — 2.10 mK and 2.35 mK, corresponding to $\tau = \Delta = 0.64$ and 0.39 mK. Both of these thermometers differ from the one used in the specific heat measurements. The corrected specific heat curve shown in Fig. 2 corresponds to $\Delta = 0.4$ mK (taking $\Delta = 0.5$ mK would lower the 10 mK value of C/RT by an additional 1% and give a constant C/RT at lower temperatures). The Grenoble specific heat data were obtained with a similar thermometer, and a similar correction seems appropriate. For this thermometer the value of T_A suggests $\tau = 0.6$ mK.¹⁷ The corrected data have not been shown in Fig. 3, but the correction would be about 50% greater than that shown for the La Jolla data.

The Bell Laboratories temperature scale was based on an LCMN thermometer (10 mole %) below 15 mK and a CMN thermometer above 15 mK. These thermometers were apparently assumed to have the same value of Δ and that value was originally chosen to make an extrapolation of measurements of the melting pressure (above 8 mK) fit the

Cornell-II data at T_A . The value of Δ was later reduced by 0.3 mK to make the lowest-temperature specific heat data linear in temperature. Since the original scale was in good agreement with the Cornell-II scale (as shown by comparison of the melting pressures) and temperatures on the later scale were adjusted downwards by a constant 0.30 mK, comparison with λ and τ for the Cornell-II scale gives $\lambda = 1.00$ and $\tau = 0.29$ mK.

On the corrected scale the overall spread in specific heat data at 10 mK is reduced to 10% (from 33%) at zero pressure, and to 6% (from 28%) at 28 atm. The remaining discrepancies in the specific heats are of the order of those in the specific heat ratios (Table II) and therefore reflect other systematic errors in the data. Furthermore, the widely divergent La Jolla and Helsinki data converge on the Cornell-II and Bell Laboratories data, for which the adjustments were small, and on our data. The latter three scales are based on both high- and low-temperature calibrations on the thermodynamic scale while the first two are based on only one or the other. The Helsinki scale is derived from Pt NMR thermometry between 2 and 7 mK. The CMN scale used in the La Jolla measurements was based on high temperature calibrations against the He vapor pressure scales. Our scale is tied to the He vapor pressure scales at high temperatures and to NO thermometry at low temperatures. The Cornell-II and Bell Laboratories scales are complementary: The Cornell-II scale gives the melting pressure-thermodynamic temperature relation from 1 to 23 mK with the major uncertainty being a scaling factor which depends on T_A . The Bell Laboratories CMN scale is based on the He vapor pressure scales at high temperature with Δ chosen to give agreement with the Cornell-II scale at T_A . The excellent agreement between melting pressures measured on the two scales provides confirmation of both. Although these considerations do not prove that the specific heat discrepancies are entirely due to temperature scale errors, they do show that obvious discrepancies between the scales in the 2-3 mK range can account for the specific heat differences when extrapolated to higher temperatures in a plausible way.

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