Nuclear Susceptibility of Liquid Helium-3 under Pressure

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(Received June 8, 1962)

New measurements of the nuclear susceptibility of liquid helium-3 between 0.045 and 1.3°K and up to 30.7 atm will be described. At the lowest temperatures, the susceptibility for all pressures has almost reached a constant value. The effective Fermi temperature T_F^{**} from these measurements is found to vary from 0.43°K at 0.5 atm to about 0.26°K at 30.7 atm. From these measurements and recent specific-heat data of several authors, the spin-dependent exchange constant is calculated and is found to decrease with increasing pressure and density. The spin specific heat calculated from susceptibility according to Goldstein's theory is compared to available data. The susceptibility results are compared to recent data of Anderson, Reese, and Wheatley.

I. INTRODUCTION

ONE of the most interesting properties of liquid helium-3 is its nuclear susceptibility. It was first measured by Fairbank and co-workers[1] at temperatures above 1°K and subsequently at lower temperatures[2] and under pressure.[3] The most striking phenomenon found was the departure from Curie's law at temperatures below 1°K corresponding to the behavior of a degenerate Fermi-Dirac gas. For the liquid under saturated vapor pressure, the effective degeneracy temperature was 0.45°K as compared to 5°K calculated for an ideal Fermi-Dirac gas having the same density and mass as liquid helium-3. This discrepancy has been explained by Brueckner and Gammel[4] and by Landau[5] in terms of a ferromagnetic exchange interaction tending to line up the nuclear spins parallel, hence tending to cancel the antiparallel alignment due to Fermi-Dirac statistics. As the pressure increases, the susceptibility per atom χ is found to increase, in agreement with Brueckner and Gammel's predictions. At the lowest temperatures reached by Fairbank and Walters, 0.12°K, the susceptibility had not reached a constant value. Anderson, Hart, and Wheatley[6] drastically extended the temperature range down to 0.03°K and measured the susceptibility at 0.2 atm by a free precession method.

In this paper we present new results of the susceptibility down to temperatures of 0.045°K and pressures up to 30.7 atm. These measurements, taken in the fall of 1961, are a continuation of Fairbank's work. They have been carried out in a modified apparatus which allowed lower temperatures to be reached. Basically, these results do not show a strikingly new phenomenon, but they were taken at sufficiently low temperatures where the susceptibility for all pressures was almost constant and they offer a comparison with Fairbank's data and with the most recent results from the Illinois group.[7] Also, they were taken at pressures higher than the minimum of the melting curve and they showed that up to about 30.7 atm at least, the liquid behaves not differently from that at pressures just below $P_{\min}=29.3$ atm. By comparison of our results to those from specific-heat experiments the correlation constant between the spins could be derived as a function of pressure and density. In agreement with the findings of other workers[7,8] no transition to a superfluid phase could be detected. According to the calculations of Nosanov and Vasudevan,[9] the susceptibility in the correlated phase should drop sharply with temperature and finally be zero at 0°K.

II. EXPERIMENTAL

The helium-3 used in this investigation was 99.1% pure from mass spectrometric analysis. The small He^4 impurity should not have an appreciable influence on the susceptibility of He^3. Also, as calculated by Edwards and Daunt,[10] there should be a phase separation at a temperature of about 0.2°K, below which the susceptibility of very pure He^3 would be recorded.

The cryogenic part of the apparatus is the same as described previously.[11] He^3 is introduced through a capillary into a cavity of about 15 mm^3 volume, surrounded by an rf coil embedded in araldite and contained in a copper capsule. The sample is in thermal contact through copper wires with a pill of chromium methylammonium alum which is cooled to 0.045°K by adiabatic demagnetization. The temperature is meas-

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[3] W. M. Fairbank and G. K. Walters, *Proceedings of Symposium on Solid and Liquid Helium Three* (Ohio State University Press, Columbus, Ohio, 1957), p. 205.
[4] K. Brueckner and J. L. Gammel, Phys. Rev. **109**, 1040 (1958).
[5] L. D. Landau, J. Exptl. Theoret. Phys. **30**, 1058 (1956) [translation: Soviet Phys.—JETP **3**, 920 (1957)].
[6] A. C. Anderson, H. Hart, and J. C. Wheatley, *Helium Three*, edited by J. G. Daunt (Ohio State University Press, Columbus, Ohio, 1960), p. 41.
[7] W. Reese, A. C. Anderson, and J. C. Wheatley, Bull, Am. Phys. Soc. **7**, 76 (1962); A. C. Anderson, W. Reese, and J. C. Wheatley, Phys. Rev. Letters **7**, 76 (1961).
[8] A. C. Anderson, G. L. Salinger, W. A. Steyert, and J. C. Wheatley, Phys. Rev. Letters **6**, 331 (1961).
[9] L. H. Nosanov and R. Vasudevan, Phys. Rev. Letters **6**, 1 (1961).
[10] D. O. Edwards and J. G. Daunt, Phys. Rev. **124**, 640 (1961).
[11] E. D. Adams, H. Meyer, and W. M. Fairbank, reference 6, p. 57.

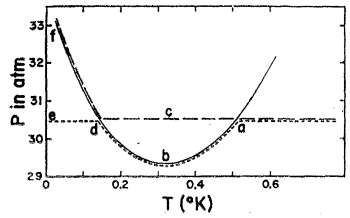

FIG. 1. Blocking of the capillary to the cavity when the melting curve is reached. Short dashed line, capillary blocks immediately; long dashed line, capillary blocks only after cell is full of solid.

ured with two Speer carbon resistors of 450Ω nominal calibrated against the magnetic susceptibility of the chrome alum. For this salt, the $T-T^*$ relation was determined in a separate experiment using as a thermometer cerium magnesium nitrate which follows Curie's law down to temperatures below 0.01°K. The carbon resistor calibration was also checked by observing the nuclear susceptibility of low density solid helium-3 which follows approximately Curie's law over our range of investigation.[7,11] While the temperature was known to be better than 5% above 0.07°K, the possible systematic error at the lowest temperatures was estimated to be less than 8%.

In Fairbank's experiments,[1-3] the nuclear resonance detection system consisted in a Rollin-type circuit, operating at 30 Mc/sec. In the present research, an improved version of Fairbank's circuit is used, which works at 3.3 Mc/sec. Nuclear resonance is then obtained in a dc magnetic field of about 1000 G. The change of the rf level in the tank circuit, when the nuclei go through resonance is detected on two oscilloscopes, where it is recorded photographically and visually and it can also be measured on a chart recorder. In the course of an experiment, when the rf current is kept constant, the susceptibility can be determined in arbitrary units as a function of T and P. In liquid He^3, the natural linewidth is less than about 10^{-4} G and the width and the shape of the signal are thus determined by the inhomogeneity of the magnetic field. Hence, the signal height, as well as the area, is a function of the susceptibility. During the experiments, the linewidth, as recorded on photographs, was found to be independent of temperature and pressure within the limit of accuracy, 3%. Hence, the height was taken to be a measure of the susceptibility. As shown by Walters[12] and by Bruce, Norberg, and Pake,[13] if the resonant LC circuit draws a constant rf current, the nuclear susceptibility is given to a very good approximation by

$$\chi=\frac{1}{K}\frac{\Delta V}{V}\frac{1}{(1-\Delta V/V)}, \tag{1}$$

where V is the rf level and ΔV is the drop of the level at the maximum of the nuclear resonance absorption. K is a constant proportional to the quality factor of the coil, the frequency, the inverse linewidth parameter, and the filling factor. For our resonance cavity, the maximum measured $\Delta V/V$ at the lowest temperatures and at 30 atm was found to be about 8%. Usually the susceptibility was measured with an rf level of about 1 mV peak to peak, which is half of the voltage at which it was just possible to perceive beginning of saturation. Saturation checks measuring the signal height versus the rf level were carried out at pressures up to 32 atm and at the lowest and highest temperatures. It was found that the spin-lattice time T_1 in the liquid, as measured by a common technique,[4,14] was almost independent of temperature and pressure, and was about 30 sec. This short relaxation time, much shorter than that obtained by Romer,[14] can be explained by wall relaxation effects.

The pressure of He^3 was measured by two Ashcroft gauges which agreed within 1%. At a pressure P above approximately 29.3 atm the melting curve of He^3 is reached.[15] If the helium cavity is cooled, there are two extreme possibilities as illustrated in Fig. 1: A. The capillary leading to the sample inside the rf cavity blocks immediately and the quantity of helium inside the cavity stays the same. When the sample is cooled, the melting curve is followed until the point d, when the pressure is approximately P again. The melting curve is then left and there is only liquid in the cavity. On the path abd, the susceptibility is that of a mixture of solid and liquid and is given by

$$\chi=x\chi_{\text{solid}}+(1-x)\chi_{\text{liquid}}. \tag{2}$$

The concentration x of the solid is determined as a function of T from the molar volumes of liquid and solid He^3 along the melting curve,[16] assuming that they are dependent on pressure, not on temperature.

B. The capillary does not block until the sample inside the cavity is solidified. Upon cooling, the pressure stays constant until the point d has been reached. Then the melting curve is followed. Hence, between a and d the susceptibility is that of solid helium, while from d to f the susceptibility is given by Eq. (2). Experimentally one can detect whether possibility A is followed or not, because the susceptibility will show a sudden increase when solid helium, which is approximately 5% more dense, has entered the cavity. In our own experiments, the cavity seems to have blocked immediately for pressures up to 30.5 atm and somewhat later in an experiment at 30.7 atm. For this last experiment the real pressure inside the cavity was calculated to be 31.1 atm at temperatures below 0.1°K using Eq. (2). Above 30.8 atm the capillary must not have blocked and solid must have filled the cavity almost completely, as will be discussed below.

In a series of experiments, the susceptibility was

[12] G. K. Walters, thesis, Duke University, 1956 (unpublished).
[13] C. R. Bruce, R. E. Norberg, and G. E. Pake, Phys. Rev. **104**, 419 (1956).
[14] R. H. Romer, Phys. Rev. **117**, 1183 (1960).
[15] D. O. Edwards, J. L. Baum, D. F. Brewer, J. G. Daunt, and A. S. McWilliams, reference 6, p. 126.
[16] E. R. Grilly, S. D. Sydoriak, and R. L. Mills, reference 6, p. 221.

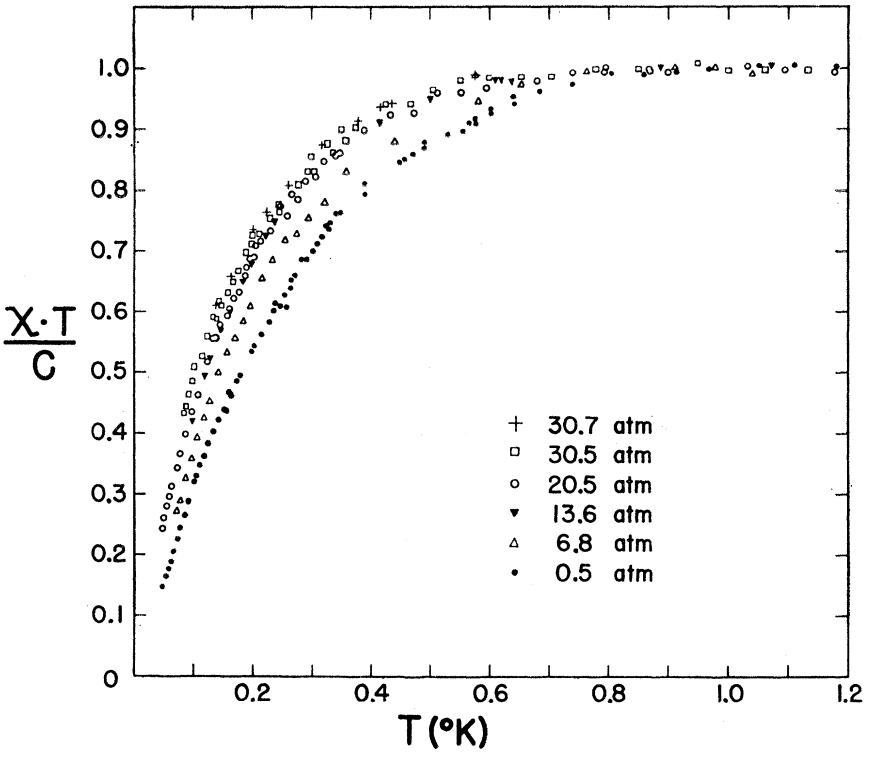

FIG. 2. The susceptibility of liquid He³, plotted as $\chi T/C$ vs T for various pressures. The pressures are those applied externally. For temperatures below 0.1°K only a few of the points are shown.

measured at several pressures as a function of temperature. Since the density for a given pressure varies at most 1% between 0.05 and 1.2°K,[17,18] the measurements at constant pressure were practically equivalent to measurements at constant density. If the capillary blocked immediately when the melting curve was reached, the density obviously stayed constant, if one neglected the small effect due to the shifting of the plug in the capillary with temperature. At pressures below 29.5 atm, several series of measurements were made by varying the pressure and keeping the temperature practically constant. Both sets of experiments were found to be consistent to better than 3%. The thermal contact between cavity and liquid helium did not seem to present serious problems. Ten minutes after adiabatic demagnetization (carried out over a period of a few minutes) the signal height of nuclear resonance had almost reached its maximum value. Data were taken 15 min after the signal had become constant, which means approximately 30 min after magnetic cooling. For every temperature, approximately 7 visual and 3 or 4 photographic readings of the ratio $\Delta V/V$ were made. The errors on the measurements of the susceptibility were estimated to be less than 3%. Heat was added to the sample between the measurements and when it was switched on, the signal decreased immediately and took a new equilibrium value within 5 min after the heat was turned off.

[17] D. M. Lee, H. A. Fairbank, and E. J. Walker, Phys. Rev. **121**, 1258 (1961).
[18] J. E. Rives and H. Meyer, Phys. Rev. Letters **7**, 217 (1961).

III. RESULTS

The question of normalization of nuclear susceptibility results has been discussed extensively by Fairbank.[3] Accordingly, we have measured in several experiments the susceptibility at constant temperature as a function of pressure, between 1 and 1.8°K and we have also measured the susceptibility at constant pressure as a function of T in this range in order to check again if it departed from Curie's law. Within experimental accuracy of about 2%, we have found the susceptibility per cm³ of the liquid helium to be proportional to the density as determined by Sherman and Edeskuty,[19] and this agrees with the earlier measurements of Fairbank and Walters.[3] Also, the susceptibility of liquid helium at 30.5 atm was found to follow Curie's law down to 0.7°K with an accuracy of about 2%. It was found that the susceptibility of liquid helium under any pressure followed Curie's law at least down to 1°K within 2 to 3%. At pressures above 31.5 atm, Curie's law was always followed within experimental accuracy down to the melting curve. Accordingly the ratio χ/C, where C is the Curie constant per atom, was taken to be unity at 1.00°K and all the results were normalized to this value, as was done earlier by Fairbank *et al.*[3]

In Figs. 2 and 3 we present our results. For temperatures above 0.2°K, the plot of $\chi T/C$ vs T is the more convenient, since it shows well the high-temperature region. For temperatures below 0.3°K, a plot of

[19] R. H. Sherman and F. J. Edeskuty, Ann. Phys. (New York) **9**, 522 (1960).

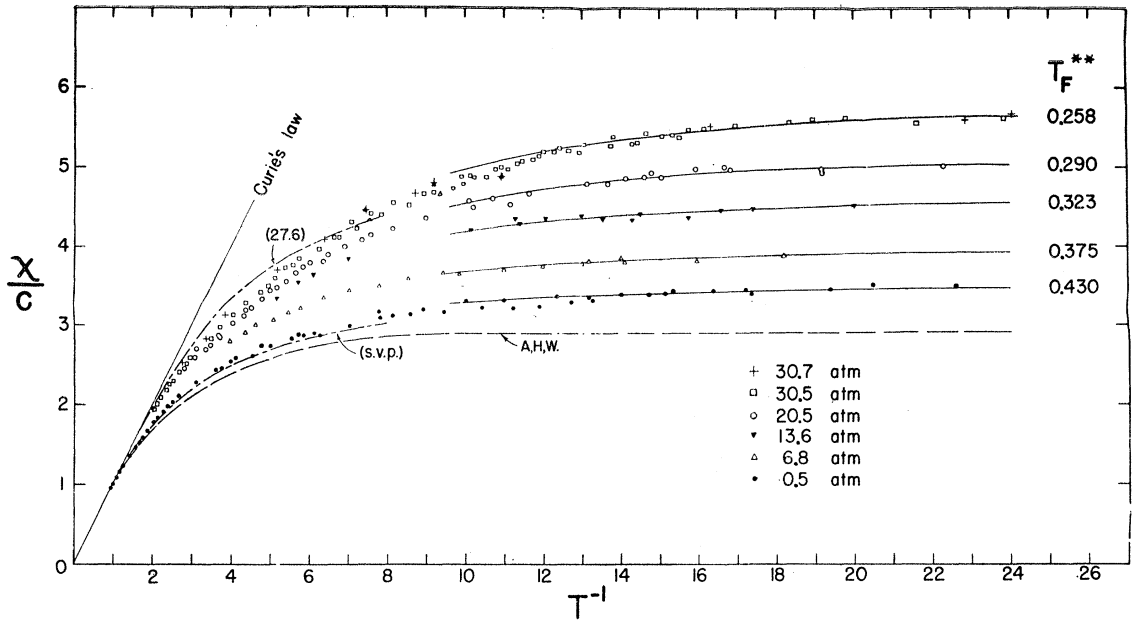

FIG. 3. The susceptibility of liquid He^3, plotted as χ/C vs T^{-1} for various pressures. The pressures are those applied externally. Dashed curve: results of Anderson, Hart, and Wheatley. Dot-dash-dot curve: results of Fairbank and Walters at saturated vapor pressure and at 27.6 atm.

χ/C vs $1/T$ is more useful. Smoothed values of our results are presented in Table I. For pressures above $P_{\min}$, the measured susceptibility is given by Eq. (2) when the melting curve is followed. Assuming that χ_{solid} follows Curie's law over this pressure and temperature range,[11,7] the susceptibility of the liquid was determined and is plotted in these figures. The maximum correction to the measured susceptibility was about 6% at 0.2°K. The results are compared to two curves obtained by Fairbank and Walters.[3] For pressures below 0.5 atm, good agreement is obtained over the whole temperature range. At 27.6 atm, the agreement is less good, but still reasonable. The results of Anderson, Hart, and Wheatley[6] at 0.2 atm, obtained from a free-precession technique, are systematically lower than ours over the whole temperature range when normalized to unity at 1°K. In Fig. 4, the susceptibility

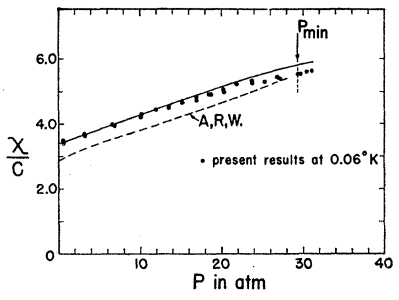

FIG. 4. The nuclear susceptibility of liquid He^3 at the lower temperatures as a function of pressure. Data at 0.06°K. Drawn curve: Susceptibility at 0.03°K and below as extrapolated from our results by means of Eq. (6). Dashed curve: Susceptibility data at 0.03°K as obtained by Anderson, Reese, and Wheatley.

at 0.06°K, when it has almost reached a constant value, is plotted against pressure. The drawn curve gives our value of χ/C vs P extrapolated to sufficiently low temperatures, when it is temperature independent. [See Eq. (6).] The recent results of Reese, Anderson, and Wheatley[7] at various pressures are qualitatively the same but their susceptibilities are smaller by about 10% on the average. It is interesting to note that for the liquid, the free-precession technique as used by Wheatley and co-workers gives a lower value for the susceptibility, while for solid He^3 at a pressure of 35 atm both their results and those at Duke[11] are in good agreement, namely, the susceptibility follows Curie's law.

At pressures above 30.7 atm the capillary suddenly did not block effectively any more and possibility B was realized. Hence, the susceptibility was that of the solid until the melting curve was reached on the low temperature side. Then the susceptibility started to depart slowly from Curie's law. The temperature dependence of the susceptibility could be interpreted satisfactorily from Eq. (2) and taking a susceptibility value for the liquid slightly larger than for a pressure of 30.7 atm. At the temperature of 0.05°K, the pressure in the cavity was then about 32.5 atm. At first, the sudden change in behavior of the capillary was not believed, because this particular capillary had been tested several times at higher pressures and had usually blocked immediately. It was thought at first[20] that the large unexpected susceptibility found in all experiments for

[20] A. L. Thomson and H. Meyer, Bull. Am. Phys. Soc. 7, 76 (1962).

pressures above 30.7 atm was due to the liquid, which would show unusual properties, as found in other experiments.[21–23] Fairbank,[24] however, was able to show convincingly that all these properties could be explained by assuming that they were those of a mixture of solid and liquid along the melting curve.

As mentioned before, the relaxation time, T_1, when only liquid He³ was in the cavity, was about 30 sec at all pressures and temperatures. When the susceptibility was measured along the melting curve, the relaxation time was too small to be measured (certainly smaller than, say, 2 sec) because of the presence of solid.

IV. DISCUSSION

At temperatures below about 0.07°K, several experiments on liquid He³ confirm the expectations from Landau's theory of a Fermi liquid. The specific heat C_v tends to the relation

$$C_v=\frac{m^*k^2}{\hbar^2}(\pi/3n)^{2/3}T=\frac{\pi^2}{2}k(T/T_F)=\gamma T \text{ ergs/atom deg} \tag{3}$$

with

$$T_F=\frac{\hbar^2\pi^2}{2m^*k}\left(\frac{3n}{\pi}\right)^{2/3},$$

where n is the number of atoms per cm³, m^* is the effective mass of the quasi-particles, and T_F is the effective Fermi temperature. m^*/m is found to vary from 2.8 to about 4.7, according to Anderson, Salinger, Steyert, and Wheatley,[23,25] when the pressure is increased from 0.2 to about 29 atm. In this pressure range, m^*/m varies from about 2.3 to about 3.5 according to Brewer and Keyston,[26] and Strongin, Zimmerman, and Fairbank.[27] Some caution must be taken when comparing the values of m^*/m, derived by different authors, as the extrapolation of their results to temperatures where C_v is really proportional to T is done from different temperature ranges. The susceptibility at low enough temperatures should follow the relation

$$\chi=\frac{3\mu^2}{2k}\frac{1}{[\pi^2k/2\gamma+\frac{3}{8}(\zeta/k)]}=\frac{3}{2}\frac{C}{T_F^{**}}, \tag{4}$$

where μ is the magnetic moment of a He³ nucleus, ζ is the exchange interaction between the spins as introduced by Abricosov and Khalatnikov,[28] C is the Curie constant, and

$$T_F^{**}=\frac{\pi^2k}{2\gamma}+\frac{3}{8}\left(\frac{\zeta}{k}\right) \tag{5}$$

is the Fermi temperature *as obtained from susceptibility data*. One should expect that as the temperature increases, the susceptibility should be given approximately by the relation derived for an ideal Fermi gas with a Fermi temperature T_F^{**}

$$\chi=\frac{3}{2}\frac{C}{T_F^{**}}\left[1-\frac{\pi^2}{12}\left(\frac{T}{T_F^{**}}\right)^2+O\left(\frac{T}{T_F^{**}}\right)^4+\cdots\right]$$

$$\text{for}\quad T_F^{**}\gg T. \tag{6}$$

Numerical values of the exact relation are tabulated by Stoner and McDougall.[29] This relation could be well fitted up to about 0.09°K to our experimental curves and these have accordingly been labeled with the appropriate T_F^{**}.[30] It should be pointed out that since the theory of the Fermi liquid is only valid at sufficiently low temperatures, one should not expect a good fit between the calculated susceptibility and the experimental values for temperatures above say $T/T_F^{**}=0.2$. For $T_F^{**}=0.43$°K, the calculated susceptibility departs from Curie's law by about 7% at 1°K, while experimentally no departure from this law could be detected.

Using the experimental values of χ and C_v, the value for the interaction constant ζ can be determined as a function of pressure and density. Since there seems to

TABLE I. The nuclear susceptibility χ/C of liquid He³ as a function of temperature for various pressures. P is the pressure applied externally. For $P>29.3$ atm the actual pressure in the cavity is smaller when one moves along the melting curve. For $P=30.7$ atm a small amount of He³ had entered the cavity during the blocking of the capillary. This effectively increased the pressure below 0.1° to 31.1 atm.

T(°K) \ P (atm) / ρ (g/cm³)	0.5 0.0830	6.8 0.0952	13.6 0.1030	20.5 0.1091	30.5 0.1165	30.7 0.1170
1.0	1.00	1.00	1.00	1.00	1.00	1.00
0.8	1.23	1.24	1.25	1.25	1.25	1.25
0.7	1.38	1.41	1.42	1.42	1.43	1.43
0.6	1.54	1.58	1.63	1.64	1.65	1.65
0.5	1.74	1.82	1.90	1.91	1.92	1.93
0.4	2.01	2.13	2.27	2.27	2.28	2.32
0.3	2.34	2.56	2.75	2.77	2.78	2.82
0.2	2.72	3.08	3.40	3.45	3.52	3.60
0.18	2.83	3.19	3.60	3.65	3.75	3.80
0.16	2.91	3.33	3.80	3.82	3.99	4.05
0.14	3.00	3.47	4.00	4.04	4.23	4.26
0.12	3.12	3.59	4.09	4.25	4.53	4.53
0.10	3.22	3.68	4.20	4.50	4.88	4.92
0.08	3.34	3.78	4.35	4.73	5.25	5.26
0.06	3.44	3.88	4.45	4.93	5.45	5.50
0.045	3.48	3.97	4.55	5.03	5.62	5.64
$T\to 0$	(3.49)	(4.00)	(4.64)	(5.17)	(5.82)	(5.84)

[21] A. C. Anderson, W. Reese, and J. C. Wheatley, Phys. Rev. Letters **7**, 76 (1961).
[22] A. C. Anderson, W. R. Abel, and J. C. Wheatley, Phys. Rev. Letters **7**, 299 (1961).
[23] A. C. Anderson, G. L. Salinger, W. A. Steyert, and J. C. Wheatley, Phys. Rev. Letters **7**, 295 (1961).
[24] H. A. Fairbank, Phys. Rev. Letters **8**, 49 (1962).
[25] G. L. Salinger, thesis, University of Illinois, 1961 (unpublished).
[26] D. F. Brewer and J. R. G. Keyston, Nature **191**, 1261 (1961).
[27] M. Strongin, G. O. Zimmerman, and H. A. Fairbank, Bull. Am. Phys. Soc. **7**, 76 (1962).
[28] A. A. Abricosov and I. M. Khalatnikov, Soviet Phys.—Uspeki **66**, 68 (1958), *Reports on Progress in Physics* (The Physical Society, London, 1959), Vol. 22, p. 329.
[29] J. McDougall and E. C. Stoner, Phil. Trans. Roy. Soc. London **237**, 67 (1938).
[30] It should be mentioned that Fairbank's value of $T_F^{**}=0.45$°K for 0.2 atm was obtained by a fit of his data with the susceptibility calculated for a Fermi gas (reference 29) at temperatures between 0.2 and 1°K.

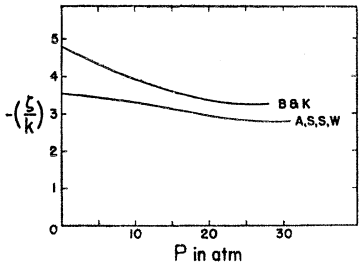

FIG. 5. The spin dependent correlation constant (ζ/k) in °K calculated from the susceptibility data and the specific-heat results of Brewer and Keyston (B.K.) and Anderson, Salinger, Steyert, and Wheatley (A.S.S. W.).

be some discrepancy between the m^*/m values found by different workers, the exact value of ζ is somewhat in doubt but probably lies between the curves shown in Fig. 5. One notes that ζ tends to decrease when the pressure is increased from 0 to 30 atm.

It is also interesting to compare the specific heat as predicted by Goldstein[31] from nuclear susceptibility, to the observed calorimetry data. According to Goldstein, the specific heat can be presented as the sum of the contribution due to the spins, C_σ and that of the "lattice" or non-spin specific heat $C_{n\sigma}$. While Goldstein's theory has been questioned by several authors,[32] some

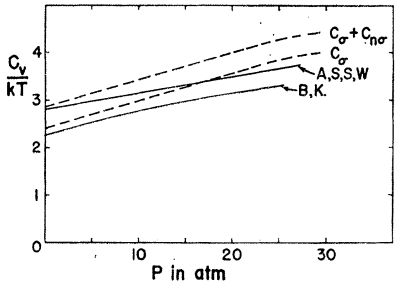

FIG. 6. The specific heat plotted as C_v/kT calculated from susceptibility measurements according to Goldstein's theory. Dashed curves: calculated values for $(C_\sigma+C_{n\sigma})/kT$ and C_σ/kT. Full lines: experimental curves of Anderson, Salinger, Steyert, and Wheatley and of Brewer and Keyston.

[31] L. Goldstein, Ann. Phys. (New York) **14**, 77 (1959).

[32] M. J. Buckingham, reference 3, p. 50. See also the discussions throughout the proceedings.

of the predicted properties have been verified rather well by experimental results at low pressures, for instance the specific heat and the coefficient of expansion at 0.2 atm.[18,33]

According to Goldstein, the specific heat of the spin system is given by

$$\frac{C_\sigma}{kT}=(\ln 2)\frac{\partial}{\partial T}\frac{\chi(P,T)}{\chi_0(P,T)}, \tag{7}$$

where $\chi_0(P,T)$ is the susceptibility of an ideal paramagnetic compound which obeys Curie's law. At low enough temperatures, when $\chi(P,T)$ is constant, one has

$$C_\sigma/kT=(3/2T_F^{**})\ln 2. \tag{8}$$

While the non-spin specific heat $C_{n\sigma}$ is estimated to be about 0.43 kT per atom of liquid He^3 at zero pressure at sufficiently low temperatures,[31] one would expect it to be somewhat smaller at higher densities. However, we will provisionally assume it to be the same for all pressures. This crude assumption will not alter the qualitative behavior of the specific heat because $C_{n\sigma}\ll C_\sigma$. In Fig. 6, $C_\sigma+C_{n\sigma}$ as derived from susceptibility results is compared to the experimental results of the different groups. As can be seen, the calculated specific heat increases relatively faster with pressure than does the experimental one, but is still reasonably consistent with the experimental data.

ACKNOWLEDGMENTS

This work has been supported by the National Science Foundation and the Army Research Office (Durham). The authors are indebted to D. C. Rorer and to Dr. P. N. Dheer for help during some of the experiments. They acknowledge gratefully discussions with Dr. J. E. Rives, Dr. H. A. Fairbank, and Dr. W. M. Fairbank. The comments on this manuscript by Dr. N. Bernardes have been much appreciated.

[33] D. F. Brewer and J. G. Daunt, Phys. Rev. **115**, 843 (1959).