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SPECIFIC HEAT AND THERMAL BOUNDARY RESISTANCE OF LIQUID He^3†

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We have measured the heat capacity of a mixture of powdered cerium magnesium nitrate (CMN) and liquid He^3 at pressures near 14 cm Hg and at temperatures extending from 0.008°K to 0.040°K. When the heat capacity of the CMN is subtracted, the resultant heat capacity is found to be linear in T within experimental scatter. No evidence has been found for a transition to the highly correlated phase predicted theoretically.[1] From the heat capacity data we derive a value of 2.35 ± 0.20 for the ratio of the effective mass of the quasi-particles to the mass of the He^3 atom. We have also measured the rate of transfer of heat across the interface between the liquid He^3 and its container and find that this rate is proportional to the differences in the fourth powers of the temperatures as expected from the simple picture of the exchange of phonons between two reservoirs at different temperatures.

The He^3 calorimeter had the following characteristics: (i) The cell containing the He^3 was cylindrical in shape, of 1.002-cm length and 0.905-cm diameter at room temperature. (ii) 300 0.004-in. diameter, 99.999% pure, enameled copper cooling wires were embedded in the inside surface of the cell, which was made using Epibond 100A.[2] (iii) He^3 was introduced by means of a 1/64-in. o.d.×0.003-in. wall Cu-Ni (70-30) tube. (iv) The heater was a 50-ohm, $1\frac{1}{2}$-in. long bifilar lead of 0.002-in. diameter "Evanohm"[3] wire coiled inside the cell. Current was conducted to the heater using 0.003-in. diameter niobium leads. (v) The cell was filled with 0.679 g of loosely packed CMN powder with sizes lying primarily in the range from 0.003 in. to 0.015 in. (vi) The cell was closed by a plug of Epibond 100A and sealed by means of a very small quantity of Epibond 104.[2] The amount of He^3 in the cell below 1°K was measured to be 0.00777 mole with an estimated accuracy of 3%. From the data of Sherman and Edeskuty,[4] the free volume of the cell was 0.294 cm^3 in reasonable agreement with the volume which was calculated on the basis of the geometry when thermal contraction and the volume of the CMN were considered.

The susceptibility of the CMN was measured using a ballistic galvanometer. It was possible to calibrate the very small amount of CMN by comparing the deflection due to the CMN with that due to the chrome alum refrigerator at a variety of temperatures from 4°K to 0.3°K under thermal equilibrium conditions and with the measuring coil and vacuum case at a constant temperature. It was essential to keep the glass vacuum case at constant temperature during calibration since its effective susceptibility was equal to that of the CMN. We assumed that Curie's law holds for CMN in the present temperature range and that, because of the nearly spherical shape of the cell, the magnetic and absolute temperatures were equal to one another. The resultant temperature calibration of the CMN was estimated to have a random error of 2%. Systematic errors due to extraneous magnetic materials or to a shift in the zero of our mutual inductances would decrease the calculated temperatures.

The He^3 was cooled: first, by a He^3 refrigerator; second, by 35.8 g of chromium potassium alum thermally coupled as tightly as possible to the cell; and third, by the CMN itself. No lead switches were used. The characteristics of this part of the apparatus will be published elsewhere.[5]

The He^3 gas was the same as that used in the diffusion and susceptibility measurements of Anderson, Hart, and Wheatley.[6] This gas had a He^4 content of less than 3 parts in 10^5. We have subsequently measured the tritium contamination of the gas. The tritium decay rate in the present cell was measured to be 300 disintegrations/sec, giving a heating rate of 2×10^{-4} erg/min.[7]

After the He^3 was initially cooled, the ballistic deflection was measured as a function of time. From time to time heat was added for short intervals. The resulting shifts in the extrapolated cooling (or warming) curves were used to obtain the temperature changes produced by adding heat. Most of the uncertainty in the data and also some systematic errors came from uncertainty in this extrapolation. The curves without external heat supplied were used to obtain the heat transfer rate across the cell-liquid He^3 interface. Even below 0.01°K the thermal equilibrium time constant of heater-He^3-CMN system was less than 100 seconds. Above 0.015°K equilibrium was attained in 20 to 30 seconds. It was this rapidly attained internal equilibrium which enabled the measurements to be made even with the tightest possible thermal coupling to the chrome alum. This tight coupling, however, did limit the region where we were able to obtain good experimental data to below 0.04°K on the high-temperature end and above 0.008°K on the low-temperature end. Temperature differences produced by heating were typically 0.4×10^{-3} °K at 0.01°K, 10^{-3} °K at 0.02°K, and 3×10^{-3} °K at 0.03°K.

We assumed that the measured heat capacity was given by $c' = \gamma T + b/T^2$, where the second term is the contribution of the CMN, and plotted c'/T vs $1/T^3$ to obtain b. The resultant value of b, 0.8 erg K°/g, is in reasonable agreement with the values reported in the literature[8] and was subtracted from the raw data to obtain the results shown on Fig. 1. The straight line through the experimental points is $C = 1.50\times10^6 T$ erg/(K°)^2, where C is the heat capacity of the He^3. This corresponds to a specific heat of $(19.3 \pm 1.6)T$ joule/mole (K°)^2 for the liquid He^3.

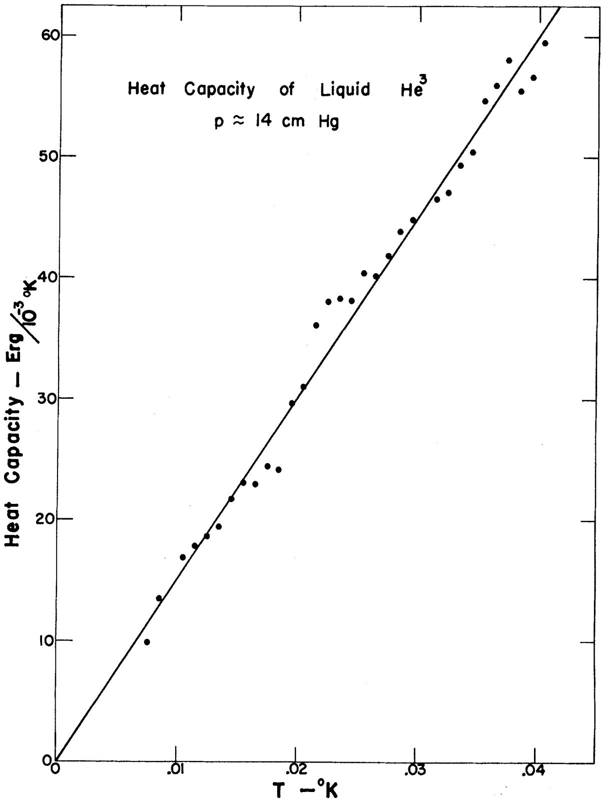

FIG. 1. Heat capacity of liquid He^3. The straight line is $C = 1.50\times10^6 T$ erg/(K°)^2. The points represent data averaged over five experimental runs.

Using the measured number of moles in the sample as given above and a molar volume of 36.5 cm^3/mole at a pressure of 14 cm Hg as deduced from reference 4, the value of m^*/m may be computed from the formula

$$\frac{m^*}{m} = \frac{\hbar^2 C}{N k^2 T m}\left(\frac{3}{\pi}\frac{N}{V}\right)^{2/3}, \tag{1}$$

where m^*/m is the ratio of the quasi-particle mass to the mass of the He^3 atom, N is the number of atoms in the sample, V is the volume, k is Boltzmann's constant, and $\hbar$ is Planck's constant divided by 2π. The result is $m^*/m = 2.35 \pm 0.20$, where the error is estimated from the errors in the cell volume, the calibration of the magnetic thermometer, and the raw data. Possible systematic errors in magnetic thermometry would serve to increase m^*/m. Brewer, Daunt, and Sreedhar[9] obtain $m^*/m = 2.00 \pm 0.05$ with convincing data, but it is possible that the specific heat is not yet linear in T at their lowest temperature, 0.085°K. We hope to revise our ap-

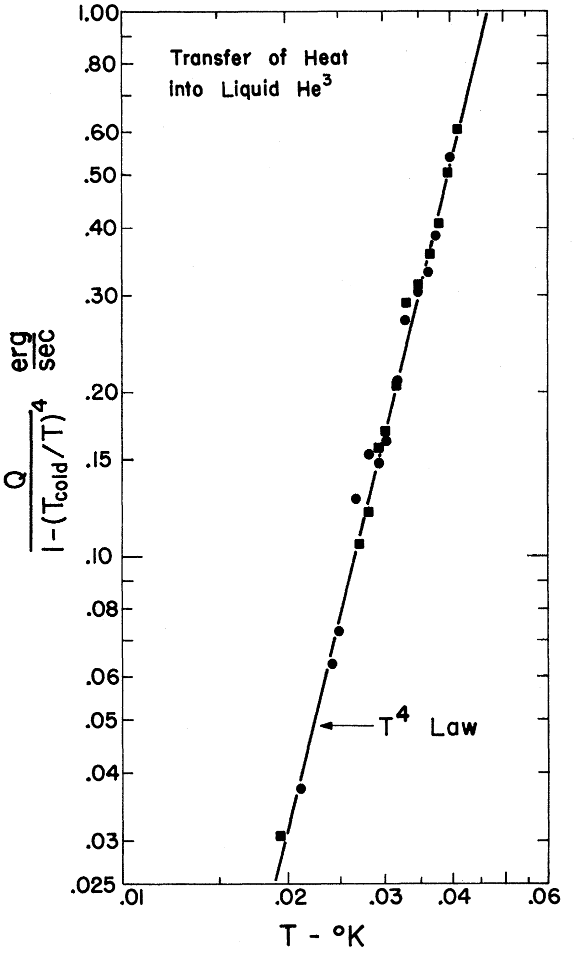

FIG. 2. Logarithmic plot of $\dot{Q}/[1-(T_{\rm cold}/T)^4]$ vs T for the heat flow $\dot{Q}$ between the cell walls and the liquid He^3. The straight line corresponds to a T^4 temperature dependence. ●—First run; ■—second run.

paratus and bridge the gap between the two measurements.

The experimental data for the heat transfer rate between the cell walls and the liquid He^3 are shown in Fig. 2. Heat flow rates $\dot{Q}$ were calculated from the measured heat capacity and the time rate of change of ballistic deflection. The data were treated as follows in order to display the temperature dependence of the heat transfer rate. For T greater than the chrome alum temperature, T_a, we estimated the alum temperature from that temperature region where T was not changing with time. We then plotted $\dot{Q}/[1-(T_a/T)^4]$ vs T logarithmically. All data above 0.022°K were treated in this way. For T less than T_a, we calculated $\dot{Q}/[1-(T/T_a)^4]$ for the same value of T_a as was used for $T > 0.022$°K for a given run, and this quantity was constant for $T > 0.01$°K. The chrome alum temperatures were adjusted slightly (by 6×10^{-4} °K in one case, 11×10^{-4} °K in the second) to obtain best agreement. The straight line drawn through the points in Fig. 2 represents a T^4 law. As plotted, the ordinate gives the rate of heat transfer from the cell surface at T into He^3 at $T = 0$. The equation of the line is $\dot{Q}/[1-(T_{\rm cold}/T)^4] = 2.0\times10^5 T^4$ erg/sec (K°)^4 = $7.2\times10^4 A T^4$ erg/sec cm^2(K°)^4, where A is the surface area of the cylindrical walls. Although the temperature dependence does not agree with that measured by Lee and Fairbank[10] at higher temperatures, it does agree with the results of the calculation of Bekarevich and Khalatnikov[11] who find the same temperature dependence as we observed. Taking for Epibond 100A a density of 1.17 g/cm^3 and a velocity of sound of 3×10^5 cm/sec as estimated from its elasticity, and substituting into the formulas of reference 11 using known constants for He^3, we find the magnitude of the heat flow predicted theoretically to be about three to six times less than we observed. This is probably reasonable agreement since the velocity of sound in the Epibond 100A is not known with any accuracy.

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[*] National Science Foundation Fellow.

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[1] K. A. Brueckner, T. Soda, P. W. Anderson, and P. Morel, Phys. Rev. 118, 1442 (1960).

[2] Furane Plastics, Inc., 4516 Brazil Street, Los Angeles 39, California. Epibond 100A has a negligible magnetism. Epidond 104 is magnetic—see reference 6.

[3] Wilbur B. Driver Company, Newark, New Jersey.

[4] R. H. Sherman and F. J. Edeskuty, Ann. Phys. 9, 522 (1960).

[5] A. C. Anderson, G. L. Salinger, and J. C. Wheatley (to be published).

[6] A. C. Anderson, H. R. Hart, Jr., and J. C. Wheatley, Phys. Rev. Letters 5, 133 (1960).

[7] We estimated the heat input using the average electron energy measured by W. L. Pillinger, J. J. Hentges, and J. A. Blair, Phys. Rev. 121, 232 (1961). We conclude that the experimental data of reference 6 were not affected by such a small amount of tritium.

[8] J. M. Daniels and F. N. H. Robinson, Phil. Mag. 44, 630 (1953); R. P. Hudson, R. S. Kaeser, and H. E. Radford, Proceedings of the Seventh International Conference on Low-Temperature Physics, University of Toronto, 1960 (unpublished).

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

[10] D. M. Lee and H. A. Fairbank, Phys. Rev. 116, 1359 (1959).

[11] I. L. Bekarevich and I. M. Khalatnikov, Zhur. Eksp. i Teoret. Fiz. 39, 1699 (1960) [translation: Soviet Phys.—JETP (to be published)]. See also I. M. Khalatnikov, Zhur. Eksp. i Teoret. Fiz. 22, 687 (1952), for some of the calculations. In our calculation we used the value of *F* given for glass

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HIGH-ENERGY X RAYS DURING SOLAR FLARES[*]

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The study of energetic particles in space has revealed many interesting phenomena concerning solar cosmic rays, proton streams, plasma clouds, and their interaction with the earth's magnetic field and its atmosphere. Measurements of the ultraviolet and soft x-ray fluxes have led to greater understanding of the processes occurring above the surface of the sun. We present some measurements which are pertinent to further knowledge of solar phenomena, namely, the detection of high-energy x rays coincident with solar flares.

Peterson and Winckler[1] have reported a short-duration x-ray burst (less than 18 sec) at balloon altitudes coincident with a class 2+ flare; neither the energy spectrum nor the time history of the event could be measured with their equipment. Energy spectrum measurements of x rays with energies up to 60 kev during three class 2+ flares have been made with rocket-borne scintillation counters.[2] Since the rockets were launched after the flares had begun, and only remained aloft for short periods, no complete time history of the events was possible. We have detected two x-ray bursts with energies exceeding 80 kev during a class 2 and a class 1 flare; spectrum measurements and the complete time history of these events were obtained. These events were recorded during an October 12, 1960 balloon flight which reached a ceiling altitude of 120 000 feet (4.8 g/cm^2) over southern Arizona.

The instrumentation consists of a NaI scintillation counter which is pointed at the sun by a tracking device described by Shechet.[3] The scintillation counter is encased in a 1-cm thick lead housing which has small holes drilled in the front face so that the field of view of the crystal is approximately a cone of 6° half-angle. The electronics shown in Fig. 1 consist of a transistorized pulse amplifier and a five-channel integral discriminator. The output pulse of each discriminator is shaped to reduce its bandwidth and

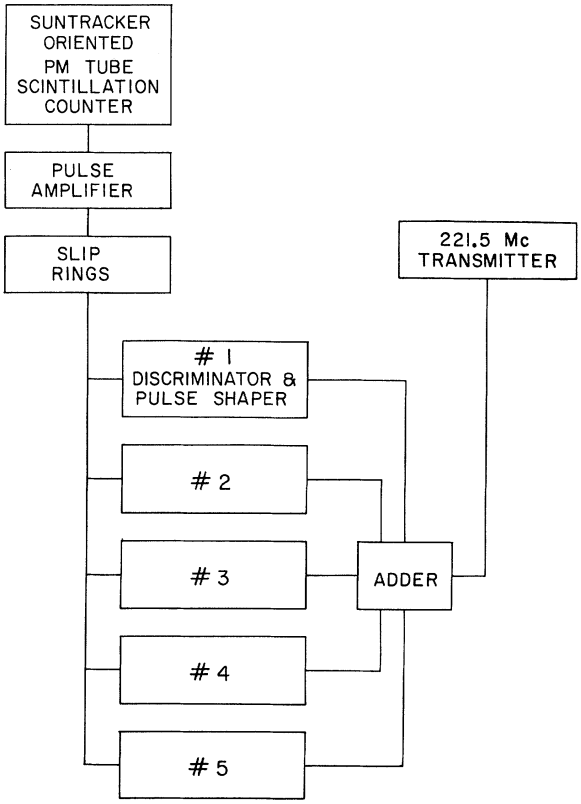

FIG. 1. Diagram of the electronics flown on the balloon.