sections perpendicular to the direction of the x-ray beam. All three sections of the crystal, which had a previous proton irradiation, showed strong coloring, whereas, in crystals which had been exposed only to x-rays, only a thin surface layer of the first section was colored, the other two sections showing negligible color-center concentration. This indicates absence of any spurious effects due to scattered x-rays, etc.

Changes in density of the clear crystals were observed after cyclotron irradiation but before irradiation with x-rays. The observed decrease in density was about four times greater than had been previously reported for heavily[2] colored crystals. A more detailed quantitative study of these effects is underway.

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Coefficient of Expansion of Liquid Helium II

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We have measured the coefficient of thermal expansion of liquid helium II from the λ point down to 0.85°K. The dilatometer was a closed system consisting of a copper chamber full of liquid helium attached to the lower end of a glass capillary in which the surface of the liquid could be viewed. The whole was immersed in a bath of liquid helium II and the procedure was to make a small measured change in bath temperature while observing the change in the position of the meniscus in the capillary. Temperatures below 1.2°K were obtained by pumping on the bath with a large diffusion pump and were measured by a carbon resistance thermometer which had been calibrated against the magnetic susceptibility of ferric alum.

Earlier density measurements[1] showed that the expansion coefficient is positive above the λ point but negative just below the λ point. Our extended measurements show that it becomes positive again below 1.12°K (Fig. 1). This was not unexpected,[2,3] since liquid helium below 1°K is very similar to a Debye solid.[4] In fact, the positive contribution which the phonons make to the expansion coefficient can be calculated from a form of Gruneisen's law,[3]

$$\alpha_{ph}=\frac{16\pi^5}{15}\frac{k^4}{h^3c^3}\left(\frac{1}{c}\frac{\partial c}{\partial p}+\frac{1}{3\rho c^2}\right)T^3, \tag{1}$$

in which α_{ph} is the phonon coefficient of expansion, c the velocity of first sound, and $\partial c/\partial p$ the variation of this velocity with pressure. This expression reduces to

$$\alpha_{ph}=1.08\pm0.04\times10^{-3}T^3\text{deg}^{-1}, \tag{2}$$

and is plotted as the dashed curve in Fig. 1.

If it is permissible to divide the measured coefficient of expansion α into separate phonon and roton contributions α_{ph} and α_r, then α_{ph} can be calculated from Eq. (2) and subtracted from α to give α_r. A calculation of $\alpha_r=-\rho(\partial S_r/\partial p)_T$, by using Landau's expression[5] for S_r and keeping his notation, yields

$$\alpha_r=\frac{2(k\mu)^{\frac{1}{2}}p_0^2\Delta}{(2\pi)^{\frac{3}{2}}\rho T^{\frac{1}{2}}\hbar^3c^2}\left(1+\frac{3kT}{2\Delta}\right)\exp\left(-\frac{\Delta}{kT}\right)\times\left[\frac{1}{2}\frac{\rho}{\mu}\frac{\partial\mu}{\partial\rho}+2\frac{\rho}{p_0}\frac{\partial p_0}{\partial\rho}+\frac{\Delta}{\rho}\frac{\partial\Delta}{\partial\rho}-1-\frac{\rho}{\Delta}\frac{\partial\Delta}{\partial\rho}\frac{\Delta}{kT}\times\left\{1+\frac{\frac{3}{2}(kT/\Delta)^2}{1+\frac{3}{2}kT/\Delta}\right\}\right]. \tag{3}$$

Within the limits imposed by the experimental errors in the various quantities, this expression is consistent with the measurements below 1.6°K if

$$[\tfrac{1}{2}(\rho/\mu)(\partial\mu/\partial\rho)+2(\rho/p_0)(\partial p_0/\partial\rho)+(\rho/\Delta)(\partial\Delta/\partial\rho)]\sim-1.5$$

and $(\rho/\Delta)(\partial\Delta/\partial\rho)\sim-0.65$.

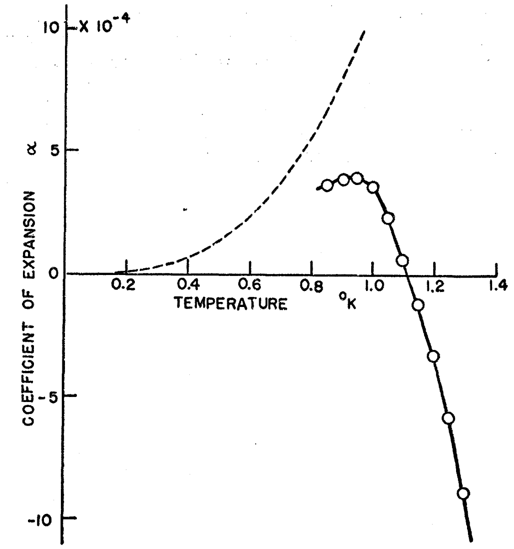

FIG. 1. The coefficient of thermal expansion of liquid helium II below 1.4°K. ○, Experimental. - - -, Phonon contribution.

Integrating α gives an accurate curve for the variation of density with temperature, and again this may be divided into phonon and roton parts,

$$\rho=\rho_0+\delta\rho_{ph}+\delta\rho_r. \tag{4}$$

By calculating $\delta\rho_{ph}$ from (2) and using it to derive $\delta\rho_r$ from (4), it appears that $\delta\rho_r$ is very nearly a linear function of the density of the normal component ρ_n. It is not possible to say whether this fact has any more fundamental significance than the approximate agreement with Landau's theory. A careful comparison of theory and experiment must await more accurate values of certain quantities, in particular the entropy, which at present is uncertain to about 10 percent.[6]

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Temperature Measurement below 1°K*

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Usually the thermometric parameters used for temperature measurements below 1°K are magnetic in character—the susceptibility, the remanence, and the area of the hysteresis loop have been so used. By carrying out thermodynamic cycles or by equivalent means, these parameters can be calibrated absolutely.[1] For temperatures down to a little way below the Curie point the results are most often presented as a $T-T^*$ relation, T being the absolute temperature, T^* the Curie temperature proportional to the reciprocal of the susceptibility. When a secondary thermometer, such as a resistance thermometer in thermal contact with the paramagnetic salt, is to be calibrated absolutely, it is usual to calibrate the resistance against T^* and then to apply the $T-T^*$ relation, usually determined in another experiment or taken from previously published data. Though there is a good deal of evidence that the $T-T^*$ relation at the very lowest temperatures depends markedly upon the thermal treatment of the salt,[2] calibrations by this method should be accurate within a few percent down to the region of, say, 0.1°K using iron or chrome alum.

The purpose of this note is to point out that it is possible to simplify this procedure and to perform the $R-T$ calibration without the need for magnetic measurements. Well-known methods can be adapted by substituting resistance measurements for susceptibility measurements, with certain practical restrictions to insure a good degree of thermodynamic reversibility. For example, using the fundamental relation $dQ=T\cdot dS$, and regarding R as a reversible temperature dependent parameter, we obtain $T=(dR/dS)/(dR/dQ)$, all referred to zero field. This is applied as follows. A series of demagnetizations is performed from known values of H/T_i (H being the magnetic field suitably corrected, T_i a temperature near 1°K), and the values of R determined at the low temperatures T attained after demagnetization. Assuming the value of the susceptibility at temperatures above T_i to be known, the entropy S at a temperature T can be calculated as a function of H/T_i and hence $(dR/dS)_{H=0}$ can be determined. The quantity $(dR/dQ)_{H=0}$ is then determined from observations of the changes of resistance produced by known heat inputs dQ at several points below 1°K.

This procedure does of course depend on a knowledge of the magnetic susceptibility of the salt above 1°K. It may be noted, however, that it is very rare indeed for an absolute susceptibility measurement to be performed as part of a $T-T^*$ calibration, the value being most often taken from other work, so the present method is no worse than usual in this respect. Deterioration of the salt—for example, as a result of prolonged exposure to a dry atmosphere—can affect the susceptibility.

This method was used for the absolute calibration, Fig. 1, of a nominal ½-watt, 100-ohm Erie "Ceramicon" radioresistor, which was soldered to metal fins embedded in a cylinder of powdered and compressed ferric ammonium alum. The cylindrical specimen of salt was of mass 6.5 g; the copper fins were of surface area 12 cm^2 and were 0.04 mm thick.

The points to be considered in such a system are (a) the rapidity of diffusion of transient temperature inhomogeneities within the salt, (b) the attainment of temperature equality between resistor and salt, (c) the temperature homogeneity within the resistor, (d) the effect on the final equilibrium temperature of the finite heat capacity of the fins and resistor, and (e) eddy current heat generation in the fins produced during demagnetization. We will now consider the conditions at 0.1°K. At this temperature the resistance of the resistor was 285 ohms and the measuring voltage across it was 100 μv. The thickness of the slabs of salt between successive pairs of fins was about 2 mm. Then (a) the observed thermal relaxation time for the thermometer to reach its steady state temperature, within the accuracy of measurement, was 7 minutes (increasing to 14 minutes at 0.05°K). This long time can however be decreased considerably by growing the crystals of salt around the fins and thus producing crystallites of large size with correspondingly larger thermal diffusivity. (b) The persistent temperature difference between the fins and the interior of the salt, caused by the steady outflow of heat from the resistor and fins into the badly conducting salt—a temperature difference which behaves as if it were due to the presence of a badly conducting layer between fins and salt—was reduced to a calculated value of not more than 0.01 percent of the absolute temperature.[3] The smallness of this difference depended on the use of a small measuring current and on the minimization of the inflow of heat down the electrical leads; these leads were constantan wires brought into thermal contact with the salt before reaching the fins. (c) Taking the thermal conductivity of the graphite of the resistor as 10^{-5} watt-unit,[4] the specific heat as 2 ergs g^{-1} deg^{-1} (using an unfavorable T^2 extrapolation of the data above 10°K),[5] the thermal relaxation time of the resistor was calculated to be less than 1 second and the temperature inhomogeneity inside it about 0.1 percent of the absolute temperature. (d) The mass of copper was 1.5 g, so the effect of the fins and resistor was to cause an increase of 0.3 percent in the final equilibrium temperature reached by a demagnetization to 0.1°K. It should be noted that this effect, in contrast to (a), (b), and (c), becomes more serious the higher the temperature, though never exceeding 1 percent. (e) Eddy current heat generation in the fins was made negligible by arranging the plane of the fins to be parallel to the magnetic field and by performing the act of demagnetization very slowly. The stray heat inflow into the salt was so small that, during tests of the reversibility of the demagnetization, times as long as 2 minutes could be taken to reduce the field to zero; further, several cycles of demagnetization and magnetization in the same field could be performed with good reproducibility of the final temperatures.

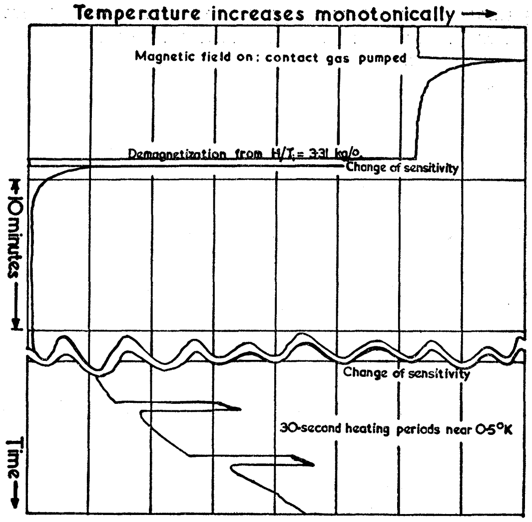

FIG. 2. Temperature changes of iron alum specimen with Allen Bradley 10-ohm resistor, taken from recording millivoltmeter.

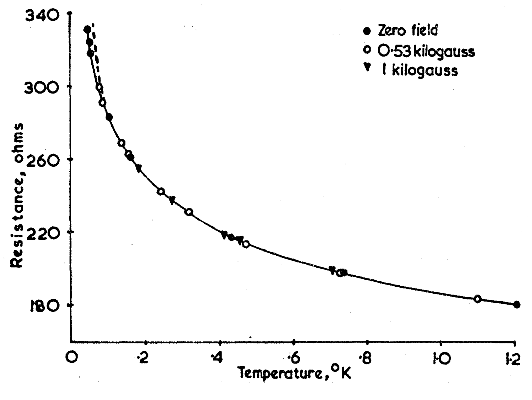

FIG. 1. Calibration curve of Erie "Ceramicon" ½-watt 100-ohm resistor.

In Fig. 1 the points are those at which tangent lines to the smoothed $S-R$ graphs were drawn. In addition to demagnetizations to zero field, final fields of 0.53 and 1.00 kilogauss were also used; the curve shows that the magnetoresistive increases of this resistor were small in these fields even at the lowest temperatures. One further point concerning the experiment is that if the salts were reproducible from run to run, there should be no reason why the value of T should not be a unique function of H/T_i; that is, in principle there should be no need to make temperature measurements on the salt at all at the low temperatures if H/T_i is known.

Using smoothed data based on published work,[6] "blind" demagnetizations of this kind using zero final field would have given correct results above 0.1°K, but below that temperature the dashed curve was obtained. It is not known, however, whether this degree of reproducibility is typical.

In the (dR/dQ) determinations the resistor itself acted as the heater, but this proved something of an oversimplification of the apparatus. It was only possible in any case because of the relatively small change of resistance with temperature which meant that the temperature difference (b) did not become serious; with an Allen Bradley 10-ohm resistor, which has a much higher slope, the measurements were difficult to control. It would have been an advantage to have incorporated a separate heater, constant in resistance, such as a constantan winding.

Figure 2 shows the temperature changes on magnetization and demagnetization of an iron alum specimen, using an Allen Bradley 10-ohm resistor, as traced by a recording millivoltmeter; subsequent heating periods, with the temperature of the resistor rising above that of the salt, are also shown. Apparatus of this kind is simple and rugged and shows a large amount of detail of behavior; it will be appreciated, for example, that a knowledge of the exact temperature of the salt immediately before demagnetization is valuable in leading to reproducible results.

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† In receipt of a grant for Further Education and Training from the Ministry of Education.

‡ Now returned to H. H. Wills Laboratory, University of Bristol, Bristol, England.

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The Specific Heat of Liquid He^3*

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THE specific heat of saturated liquid He^3 containing less than 0.1 percent He^4 has been measured from 0.54°K to 1.7°K. The results were presented at the Third International Conference on Low Temperature Physics and Chemistry and are in general agreement with data reported there by two other groups of workers.[1]

The warmup rate $\dot{T}$ of liquid He^3 in a vacuum-jacketed $\frac{3}{4}$-cc copper sphere was measured as a function of N, the total number of moles of He^3 in the system. The He^3 was cooled below the surrounding He^4 bath temperature by pumping. The heat flux to the liquid $\dot{Q}$ was measured and a plot of $\dot{Q}/\dot{T}$ *versus* N yielded a straight line. The slope, when corrected[2] for vapor warming and for evaporation into the changing amount of vapor space within the sphere, equals the specific heat. This correction varied from 2.5±0.05 percent of C at 0.54°K to 40±1 percent at 1.7°K. With this method the effects of the noxious volume outside of the sphere and of the specific heat of the calorimeter are eliminated because they do not depend upon liquid level.

Measurements were made from 1.05°K to 1.7°K with $\dot{Q}$ supplied by an electrical heater. $\dot{T}$ was measured by the vapor pressure rise and averaged about 1° per hour. Each point is based on six warmups. The results are given in Table I.

TABLE I. Liquid He^3 specific heats measured with heater.

T°K	1.069	1.157	1.256	1.364	1.453	1.528	1.609	1.695
$C\dfrac{\text{cal}}{\text{mole deg}}$	1.06	1.12	1.19	1.25	1.35	1.44	1.46	1.54

TABLE II. Liquid He^3 specific heats measured without heater.

T°K	0.540	0.629	0.748	0.804	0.872	1.251
C/L deg^{-1}	0.109	0.110	0.110	0.107	0.111	0.123
$C\dfrac{\text{cal}}{\text{mole deg}}$	0.83	0.89	0.92	0.92	0.98	1.22

To reach lower temperatures, the heater was removed and $\dot{Q}$ derived from the measured normal heat leak. The sphereas w filled with iron ammonium alum at 55 percent packing for temperature measurement by the standard ballistic method. The salt was calibrated above 1°K against the Argonne He^3 vapor pressure equation.[3]

The average heat leak was determined from: ΔN, the number of moles of He^3 pumped during cooldown between successive warmups over the same 0.05° interval; the time between identical temperatures on these warmups; and the average latent heat over the interval. A correction was applied to the observed average heat flux for the measured 2 percent reduction in flux during cooldown. Since $\dot{Q} \propto L$, only C/L is measured directly. For L we used values calculated from an equation fitting preliminary vapor pressures measured down to 0.5°K. Each point is based on at least twelve warmups. The results are given in Table II.

Entropy differences in the range 0.5 to 1.7°K can be calculated from these data. When combined with our preliminary vapor pressure data we find the value of entropy at 0.50°K to be 1.38 ±0.04 cal mole^{-1} deg^{-1}. By coincidence this is just equal to the nuclear spin entropy, $R\ln 2$. Data from a few warmups starting at 0.4°K indicate that the entropy has decreased to 1.20±0.06 at 0.4°K, a value significantly below $R\ln 2$. Hence, as qualitatively predicted by Pomeranchuk,[4] nuclear spin alignment must begin at or above 0.5°K, and a melting-pressure minimum would be expected at this temperature. The reported[3] apparent constancy of melting pressures below 0.5°K is consistent with the existence of a minimum, since the blocked-capillary technique used could not detect a rise in melting pressures below the temperature of a minimum.

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Directional Properties of the Cyclotron Resonance in Germanium*

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CYCLOTRON resonance[1] has been observed at 8895 Mc/sec in relatively pure *n*-type and *p*-type germanium at liquid helium temperatures. The samples studied were rods of approximately 1 mm square cross section, placed in the center of a rectangular cavity $\frac{3}{2}$ wavelength long. The sample occupied nearly the full height of the cavity with the rod axis in the direction parallel to the rf electric field. A transverse dc magnetic field was applied to the sample. The axis of the rod was cut along a [110] direction, so that by rotating the sample, the magnetic field could be lined up with all directions in the (110) plane, including a [100], a [111], and a [110] direction.

The resonance data were taken as a function of magnetic field, by means of an automatic recording system. The rf power down