IV. LOW TEMPERATURE PHYSICS

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A. SUMMARY OF PROGRAM OF LOW TEMPERATURE PHYSICS

The last program summary was given in the Quarterly Progress Report of January 15, 1954. That statement is brought up to data in the light of progress during the past two quarters.

Liquid Helium Research. The study of the properties of liquid helium has reached a turning point in the results of Mr. Chase, reported below, which show a double peak in the attenuation of first (ordinary) sound in liquid helium in the neighborhood of 0.8°K to 1.0°K. These peaks show the region of temperature where the relaxation time of the process causing attenuation is of the order of the period of the sound waves used. The display of two clearly resolved peaks indicates two relaxation processes, suggested by Khalatnikov (1)[*] to be attributable to phonon-phonon and phonon-roton collisions. Maurer and Herlin (2) noted a possibly related effect in the second-sound velocity. A linear superposition of phonon terms and terms extrapolated from the high-temperature excitations could not explain the sudden onset of the rise of second-sound velocity in this temperature region. The experimental curve suggested strongly that an interaction between the phonons and the high-temperature excitations caused the latter to disappear much more rapidly with decreasing temperature than was the case before the interaction region of temperature was reached. Chase's results indicate that this interaction may increase the rate of change of the relaxation time with temperature variation. The existence of strong interaction between phonons and rotons is indicated by a quantum hydrodynamical calculation by Ziman (3) whose interaction terms are so strong, in fact, that some doubt is cast on even an approximate validity of independent phonon and roton excitations in the transition region.

The follow-up of these results will be undertaken by Mr. Whitney, who has been constructing apparatus for second-sound measurements as a function of pressure in the demagnetization range. His apparatus is readily adapted to first-sound attenuation measurements, and it appears wiser to be content with the accuracy of Mayper's results on second-sound velocity for the time being and to follow the program opened by Chase's measurements. The importance of measuring the pressure dependence of effects in the transition region between phonon and roton behavior, as pointed out by Maurer and Herlin (2), lies in the opposite effects of pressure on the two excitations. The large compressibility of liquid helium leads to a rapid variation of first-sound velocity with pressure,

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[*]References for section IV are given on page 27.

and therefore to a rapid decrease in the phonon density with increasing pressure. On the other hand, the roton density is reduced by increasing pressure. The identification of Chase's peaks in sound attenuation between phonon and roton relaxation effects can therefore be accomplished by this experiment.

Phonon-roton relaxation effects may be an important probe into the nature of rotons, which are as yet little understood. Phonons, on the other hand, are fairly well known. In order to determine the phonon-roton relaxation parameters as a function of temperature from attenuation measurements, other relaxation processes must be sifted out. The pressure dependence of attenuation, as noted, will separate the phonon-phonon relaxation terms. Viscous attenuation must be separated with the aid of a knowledge of the viscosity, which is not satisfactorily known from oscillating disc measurements because of the entrance of the normal fraction of the fluid density into the experiment. The constant rotation viscosimeter reported by Mr. Kolm below may clarify the nature of viscosity in liquid helium to the extent that the roton-phonon relaxation may be completely separated from Chase's data.

Resistance Minimum Effect. Mr. Huber has improved the thermometry of the experiment measuring the thermoelectric power of magnesium showing a resistance minimum effect. He reports below a more accurate measurement of this quantity as a function of temperature. This measurement completes a survey of the thermal and electrical transport properties of this substance; a few tentative conclusions may be drawn and the way pointed for further work.

The only serious theory of the existence of the resistance minimum effect that has been put forth to date is that of Korringa and Gerritsen (4). They postulate the existence of electronic states at the Fermi surface which have a localization in a volume of the order of the volume per impurity atom. If the impurity atom is magnetic, magnetic and exchange interaction with the electronic spin splits this state slightly into two new states above and below the Fermi surface by an amount ϵ_1. The splitting increases with increasing impurity concentration because of the degree of localization specified in the postulate. These states lead to resonance rearrangement scattering of the conduction electrons, and the small value of ϵ_1 causes the rise in resistance at low temperature. At still lower temperatures a maximum is reached, below which the resistance falls off rapidly. The temperature of the maximum is a measure of ϵ_1, and the concentration dependence of this temperature, as measured by Gerritsen and Linde (5, 6, 7), shows the behavior expected from the theory. The theory accounts, too, for the large negative magneto resistance found in these substances.

The thermoelectric power is also in qualitative agreement with this theory. This effect, unlike the other transport quantities, depends on the slope of the mean free path as a function of energy. The anomalously large thermoelectric power found in our experiments is indicative of a large energy derivative of the scattering cross section,

which is to be expected from the resonance nature of the scattering.

A comparison of our magnesium containing dilute amounts of manganese may be made with the alloys of Gerritsen and Linde of noble metals with a transition metal.   Our resistance-vs-temperature curves show no maxima, which indicates a value of ϵ_1 lower than 1 °K in temperature units.   Borelius et al. (8) and Keesom and Matthijs (9) have also found high thermoelectric powers in such alloys, but none so large and persisting to so low a temperature as those found by us in magnesium.   The low value of ϵ_1 for magnesium would also explain this behavior.

Experiments that are yet to be performed on our magnesium alloys include further measurements of thermoelectric power in samples with a variety of impurity concentrations, extension of the temperature range of the resistance measurements into the demagnetization range below 1 °K to find a possible maximum and therefore determine ϵ_1, measurements of magneto-resistance effects, and Hall effect measurements to detect the difference between effects caused by scattering and those caused by state density modifications.   Mr. Wright,   who has been designing equipment for mutual inductance measurement in the presence of a magnetic field, is investigating the feasibility of the latter two experiments, using the induction method of Rorschach and Herlin (10).   In addition to these experiments, Mr. Huber (below) has pointed out the possibility of using measurements of Peltier heating along with thermoelectric power as an absolute thermometer at low temperatures.   The persistence of the thermoelectric power to the low temperature region makes such a thermometer possible.   This thermometer can be used to calibrate secondary resistance thermometers in the demagnetization range and possibly can be used to check the temperature determinations made with magnetic salts. We do not have sufficient staff to carry out all of this work immediately, but we hope to do as much as possible.

Properties of Paramagnetic Salts.   Our present objective is to construct apparatus necessary to measure the thermodynamic equation of state of paramagnetic salts.   This function is then related through statistical mechanics to the elementary excitations of the salts, which are of fundamental interest.   The results of paramagnetic resonance experiments may then be correlated with the thermodynamic properties.   However, the interactions between paramagnetic ions, especially those leading to cooperative transitions, are not given by the usual resonance experiments, and the thermodynamic properties of the salt constitute our main source of information on these phenomena.

Thermodynamic properties of a substance measured in temperature ranges above that obtained by adiabatic demagnetization are normally expressed in terms of the temperature, since thermometry is a relatively routine procedure in this range.   Below 1 °K, however, a different method is necessary, since the ideal gas thermometer used as a fundamental standard above 1 °K fails below this mark.   Since the process of adiabatic demagnetization leaves the entropy constant, the obvious procedure is to use entropy

rather than temperature as the thermal independent variable. Expressed in terms of the fundamental thermodynamic equation

$$dU = TdS - MdB$$

where U is the internal energy, T the temperature, S the entropy, M the magnetization, and B the magnetic induction, it is seen that temperature as a function of field and entropy is to be regarded as one of the differential coefficients for the equation of state U(B, S) and therefore as a dependent variable. The emphasis put upon measurement of thermodynamic temperature by those working in this field is therefore not a narrow emphasis upon thermometry, but rather a determination of a property related directly to the fundamental excitations of the salt.

Our experimental method is to measure the adiabatic susceptibility of the salt as a function of entropy and magnetic field. This quantity is proportional to $(\partial M/\partial B)_S$, and may be measured by a sensitive mutual inductance bridge. While the details of the interpretation of the experimental data (11) will not be given here, we may state that the function M(B, S) may be obtained from the susceptibility, from which we have

$$U(B, S) = -\int_{S=constant} MdB + f(S)$$

The function of integration is evaluated at high temperatures where the properties of the salt are known. This method differs from calorimetric methods in using only magnetic measurements. The main experimental difficulty is to measure small mutual inductance changes in the presence of a large magnetic field, which tends to introduce noise into the mutual inductance bridge if the field is not held extremely constant in time. Mr. Jennings has carried out the design and construction of the major components necessary to accomplish this purpose, as reported below.

B. THE VISCOSITY OF LIQUID HELIUM

Two modifications have resulted in decreasing mechanical noise by about two orders of magnitude. First, the entire apparatus, which weighs 1500 pounds, was mounted on rubber diaphragms covering apertures in a pressure system of sufficiently large volume to provide a resonance period of 6 sec for motion in the vertical direction. With these "shock mountings" in operation, it was found that the residual mechanical noise is caused mainly by the boiling of the liquid nitrogen in the outer dewar flask. By sealing the mouth of this dewar and pumping off the vapor for a brief period it proved possible to reduce the temperature sufficiently below the normal boiling point that the liquid nitrogen remains completely quiescent for about 30 minutes, even with the solenoid in operation. Moreover, electrical noise in the control circuit has been decreased substantially by converting all but the final stage of the servomechanism to battery operation.

One helium run has been made with these improvements in effect. The points representing rotor speed as a function of angle of rotation follow a straight line to within 0.5 percent, representing a very substantial reduction in scattering. The viscosity calculated from the slope of these lines is 40 micropoise at two temperatures, although it should have been about 20 micropoise in the first case (2.17°K) and about 12 micropoise in the second (1.97°K), according to previous measurements made by the oscillating disc method. The first of these two measurements was continued until the liquid helium level had dropped to below the rotor, and the damping line shows a corresponding change in slope; the new slope indicates the correct viscosity for gaseous helium at the temperature in question, about 5 micropoise.

These observations clearly indicate that the excessive viscosity values observed must be ascribed to an effect of the liquid helium itself. Future runs will determine whether or not any damping is being introduced by thermomechanical flow past the rotor in an axial direction.

<div align="right">H. H. Kolm</div>

C. MEASUREMENTS OF SECOND-SOUND PULSE AMPLITUDES IN LIQUID HELIUM II

Second-sound pulse amplitudes as a function of power input have been remeasured in the range between 1 15°K and 0.9°K, care being taken to exclude possible sources of error. The departures found previously (12) were still found to hold qualitatively but to a smaller extent quantitatively. At 1.16°K all points were still observed to lie very close to the theoretical points calculated on the basis of the propagation attenuation factor (12). From 1.10°K to 1.00°K, however, the observed points were found to lie about halfway between the two sets of theoretical values calculated, respectively, on the basis of a reflection loss factor and a propagation attenuation factor. The difference between the observed point and either the upper or lower theoretical point was about 6 percent. This might indicate a departure of this amount from reversibility in the generation of second sound in this temperature region or possible error of this amount in the values of the physical constants of liquid helium used in the theoretical formula for pulse height generation (12, 13). On the other hand, values of second-sound velocity recently measured by de Klerk, Hudson, and Pellam (14) differing by 5 percent at 0.90°K from the values used in the above formula would cause the results at 0.90°K to exhibit the same departure described above for the results from 1.10°K to 1.00°K. Reflection losses are not considered to be significant because of the very high thermal impedance of the solid bakelite receiver backing in series with its boundary layer impedances on either side (15) as compared to the impedance of the liquid helium itself to the second-sound pulses.

Measurements were made at 1.2°K, 1.0°K, and 0.93°K after the sides of the second-sound tube had been covered with a layer of vaseline to lessen contact between helium inside the tube and the bath outside. The attenuation of the second-sound pulses was about halved after this treatment. The pattern of the results was similar to the previous case, however. The measured pulse amplitudes at 1.2°K and 0.93°K were close to the lower theoretical values, whereas the pulse amplitudes at 1.0°K were quite near the higher theoretical values.

Wide pulses of second sound of about 1200 μsec duration had been observed to suffer considerable decline of the top of the pulse, or differentiation, before the vaseline application. After the vaseline application, however, this effect was reduced a great deal. Since the decline of the pulse top with time and the negative excursion at the end of the pulse indicate an attenuation of the low-frequency components relative to the high-frequency components, a possible explanation would lie in the spreading of the beam through the edges of the second-sound tube. This would be greater for the longer wavelengths or lower frequencies. Many of the significant wavelengths in the second-sound pulse were equal to or greater in magnitude than the transmitter dimensions and would spread greatly in an open vessel over the distance from transmitter to receiver. The vaseline application had the effect of better sealing the second-sound tube to spread of the waves outside it. (The pulse-top decline was not traceable to the instrumentation.)

B. Bernstein

D. ULTRASONIC PROPAGATION IN MAGNETICALLY COOLED HELIUM

Measurements have been made of the velocity and absorption of first sound in liquid helium at temperatures between 0.1°K and 1.1°K by using a pulsed ultrasonic technique at 12.1 Mc/sec similar to that employed earlier (16). The helium was cooled by the adiabatic demagnetization of a paramagnetic salt.

The apparatus, shown in Fig. IV-1, is essentially the same as one originally designed by Dr. J. Ashmead. The inner can B is supported by a thin-walled stainless-steel cone E. A similar cone F serves to isolate the inner chamber from the surrounding helium bath during demagnetization and may be raised by means of a thin-walled tube extending to the cryostat head to admit helium to the apparatus and for the removal of heat of magnetization. Leads for the ultrasonic etalon D and a resistance thermometer (not shown) were brought in through the cupernickel tube G, which was then plugged with vaseline.

Temperatures were determined from the susceptibility of the paramagnetic salt, which was measured with an ac mutual inductance bridge. The accuracy is estimated to be ± 0.02°K. Demagnetizations were performed from a starting temperature of 0.9°K with a field of 6200 gauss. The lowest temperature reached was 0.10°K; the warming time was more than an hour from this temperature to bath temperature.
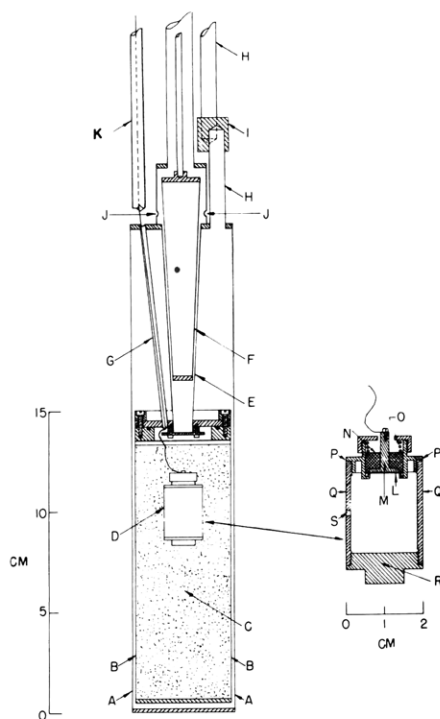
Fig. IV-1

The demagnetization cryostat. A, B, concentric cans; C, paramagnetic salt; D, etalon; E, F, thin-walled cones; G, vaseline-filled tube for leads; H, pumping tube; I, radiation trap; J, holes to admit helium; K, coaxial cable. Inset: The etalon. L, quartz crystal; M, electrode; N, bakelite insulator; O, beryllium-copper spiral spring; P, brass case; Q, brass tube; R, reflector; S, hole to admit helium.
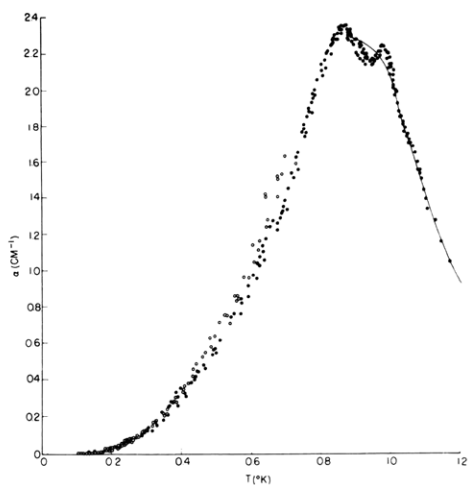

Fig. IV-2

Attenuation of sound in liquid helium at 12.1 Mc/sec. Open dots, path length = 3.94 cm; solid dots, path length = 1.96 cm; solid line, earlier results.
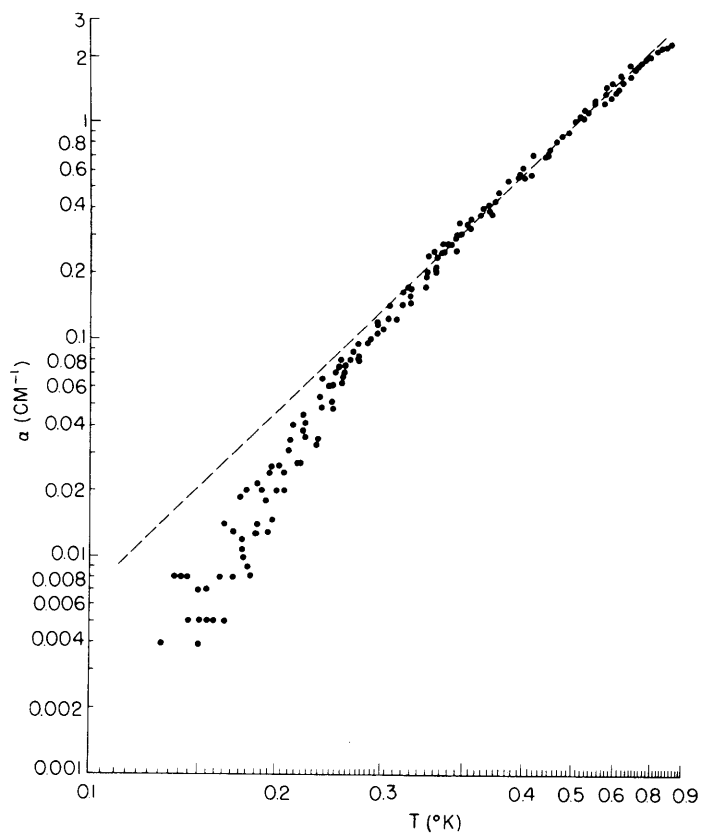
Fig. IV-3

Attenuation of sound in liquid helium at 12.1 Mc/sec.
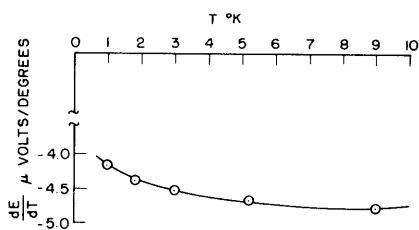The slope of the dotted line is 2.8.

Fig. IV.4

Thermoelectric power for a lead-magnesium thermocouple.

The results of these measurements are shown in Fig. IV-2. The open circles represent points taken with a path length of 3.94 cm; the solid circles were taken with a path length of 1.96 cm. The full curve reproduces the results of earlier measurements by the present author (16). The absolute values have been adjusted to agree with the earlier results above 1.2°K.

The most significant feature of the curve of Fig. IV-2 is the presence of the double maximum in the attenuation around 0.9°K. This provides direct evidence for the existence of two relaxation times governing the attenuation of sound, in agreement with the prediction of Khalatnikov (1). A detailed comparison of the results with this theory is made difficult by the fact that the relaxation time for the processes responsible for viscosity becomes comparable with the relaxation times given above in the neighborhood of 0.9°K. This makes the fraction of the attenuation due to ordinary viscosity difficult to determine. The error resulting from neglecting viscous attenuation entirely is rather small, however, so that an approximate estimate of the parameters in the Khalatnikov theory can be made. Such a calculation suggests that the value of Δ (one of the parameters in the Landau energy spectrum for rotons (17)) used by Khalatnikov (1952), is somewhat too small, and that the present measurements might provide the most sensitive means of evaluating this parameter. A preliminary estimate gives $\Delta = 9.2$°K.

Figure IV-3 shows the results replotted on a logarithmic scale. From this diagram it may be seen that between 0.3°K and 0.8°K the attenuation follows a simple power law. The slope of the dotted line through these points is 2.8. Below 0.3°K this dependence changes, and the attenuation varies considerably more rapidly with temperature. It is perhaps significant that this occurs just in the region where the phonon mean free path is becoming of the order of centimeters, and where the velocity of second sound is rising from $u_1/3$ to approximately u_1.

The velocity measurements were not particularly accurate at these temperatures but were of value in verifying that no gross changes in the velocity take place below 1°K. Within the accuracy of these measurements (about $\pm$ 2 percent) the velocity is independent of temperature below 1°K, and has the value 240 $\pm$ 5 m/sec.

C. E. Chase

E. THERMOELECTRIC POWER OF MAGNESIUM

The apparatus used to measure the thermoelectric power of the magnesium-lead junction, reported by M. A. Herlin (13), has been rebuilt in order to achieve lower temperatures and to allow calibration of carbon resistance junction thermometers in a higher temperature range. Previous measurements have been extended and checked to cover the range 1.0°-10.0°K and the thermoelectric power of the original magnesium-lead junction is plotted in Fig. IV-4 for this temperature region.

The behavior is anomalous in two respects: (a) the thermoelectric power is usually

large, and (b) there is very little variation with temperature. The results of Borelius et al. (8) and Keesom and Matthijs (9) show extremely rapid decrease of $|dE/dT|$ with temperature below 10-20°K for copper with added paramagnetic impurities. The resistance of this sample of magnesium was measured below 4.2°K by Maurer, and the minimum effect indicates a manganese impurity content of approximately 0.08 percent.

Separate measurements have been carried out on the Peltier heating effect at the lead-magnesium junction in order to check the validity of the first Thompson relation $dE/dT = \pi/T$, where π is the Peltier coefficient. The results at two temperatures are listed below.

Temperature	π/T (heat measurement)	dE/dT (emf measurement)	Experimental Accuracy
2.71°K	-4.5 μvolts/degree	-4.6 μvolts/degree	5 percent
5.08°K	-4.4 μvolts/degree	-4.6 μvolts/degree	20 percent

These results would indicate that Peltier heating measurements below 1°K may be feasible and that a thermodynamic temperature scale could be obtained by measuring the Peltier coefficient as a function of the thermoelectric potential. This follows from the first Thompson relation, since

$$\int_{E_o}^{E} \frac{dE}{\pi(E)} = \int_{T_o}^{T} \frac{dT}{T}$$

gives an expression for the temperature in the form

$$T = T_o \exp\left[\int_{E_o}^{E} \frac{dE}{\pi(E)}\right]$$

measuring E to ± 0.01 μvolt would determine T to approximately 0.002°K at 4°K, but the accuracy is unknown at lower temperatures.

E. E. Huber, Jr.

F. MEASUREMENT OF THE THERMODYNAMIC EQUATION OF STATE OF PARAMAGNETIC SALTS

Two components of the experimental apparatus have been satisfactorily completed. The mutual inductance measuring equipment includes a detector capable of detecting

10^{-9} volt at an impedance level of 10 ohms with a bandwidth of 2 cps at 33 cps. The detector consists of a transformer with a turns ratio of 500, a preamplifier, and a selective amplifier whose output is viewed on an oscilloscope. The preamplifier makes use of a type 5678 subminiature pentode whose noise output voltage, when referred to the input, is lower by a factor of 4 than that of any other tube tried in this laboratory. This behavior is reproducible with this tube type.

A liquid nitrogen cooled solenoid which delivers 10 kilogauss with an input power of 800 watts has been constructed. The inside diameter of this solenoid is 2 cm; the length is 6.7 cm. By suitably spacing the turns, the field is made sensibly uniform for 2 cm along the axis. The sample is only 7 mm in diameter.

<div align="right">L. D. Jennings, Jr.</div>

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