III. SOLID STATE PHYSICS

A. PROPERTIES OF MATTER AT LOW TEMPERATURES

1. Helium Liquefiers

Staff: R. P. Cavileer
S. Ames
J. Tooney, Jr.

With no major overhauling, the first liquefier is, at the end of this quarterly period, on its seventy-third run. As we stated in the last progress report, we can still see no reason for immediate breakdown. An increasing amount of oil, however, has been noticed seeping through the seal in the cross-head on the piston rod. If this discharge exceeds a certain amount, it will pass the coupler of the cross-head rod to the engine rod and will get to the stuffing-box plate where it will creep on to the valve rods and foul them. A modification of the coupler and piston rods will allow for the type of oil cup installed on the valve rods as mentioned in the last report.

Practically all of the runs during the past several months have been made for the purpose of transferring liquid helium to an external Dewar. As the amounts needed have not been excessive, it has been found that the most practical method is to use the auxiliary liquefying lines included with the cryostat. This method gives a much higher efficiency of transfer than that of using the transfer tube mentioned in the last report which transferred the liquid from the main reservoir.

Since practically all of our time has been spent in making runs with the first liquefier, there has been little opportunity to devote to testing the second liquefier, but two useful runs, however, have been made with it. A very satisfactory rate of liquefaction was obtained running with a cam setting which allowed an over-pressure on the engines, i.e., 220 lb/in.^{2} instead of the normal 200 lb/in.^{2}.

2. Surface Impedance of Tin

Staff: Professor J. C. Slater
Dr. P. M. Marcus
Dr. E. Maxwell

The previously reported measurements and calculations on the surface impedance of tin at 24000 Mc are being prepared for publication. Included in the report will be a comparison of the data with measurements of other experimenters, a review of the Sondheimer and Reuter theory of the anomalous surface impedance of metals when the electronic mean free path is large compared to the classical skin depth and of the assumptions underlying the theory. A discussion will be given of the field distribution inside the metal in the anomalous region, various methods of calculating physical constants from the data (number of free electrons, mean free path, static superconducting skin depth) will be compared, including the methods of London and Pippard. The extension of the theory to the superconducting state will be given as well as a derivation by a kinetic method of the basic integral equations for the field of Sondheimer, Reuter, and Pippard.

The following comparison of static superconducting penetration depths calculated from our data with values obtained by other investigators by entirely different methods, is of interest. The table lists values of the change $\Delta\lambda$ in static penetration depth referred to 2.3°K for various temperatures.

$$\Delta\lambda = \lambda(T) - \lambda(2.3^{o}K)$$

	$\Delta\lambda$ in units of 10^{-6}cm			
$T^{o}K$	Desirant and Shoenberg[1]	Pippard[2]	Laurmann and Shoenberg[3]	Maxwell[4]
3.009	2.32	1.2	2.4	1.1
3.559	8.11	6.2	7.5	7.5
5.588	9.93	7.3	9.2	8.8
3.649	14.03	9.9	12.3	12.6
3.667	22.77	11.2	13.9	14.9

The agreement is considered good.

A comparison has also been made of our surface reistance data at 24000 Mc/sec with that of Pippard at 1200 Mc/sec. These data are consistent with the frequency dependence given by the London theory. Both sets of data lead to values of λ which agree within 15 per cent when the London theory is used to reduce observed values of surface resistance to penetration depths.

---

1. M. Desirant and D. Shoenberg, Nature, <u>159</u>, 201 (1947).
2. A. B. Pippard, "Resistance of Superconducting Tin and Mercury at 1200 Mc/sec.
3. E. Laurmann and D. Shoenberg, Nature <u>160</u>, 747 (1947).
4. E. Maxwell, "Surface Impedance of Tin at 24,000 Mc/sec in the Superconducting and Normal States", Ph.D. Thesis, MIT, 1948.

III. A. 3. Resistivity of Normal Conductors

Staff: Professor J. C. Slater
W. B. Nowak
I. Simon

The techniques of absolute Q measurement at 24000 Mc/sec have been refined so that the precision of a single measurement is about ± 1 per cent and the reproducibility with different experimental arrangements is about ± 5 per cent.

Results on a TM_{050} cylindrical cavity of copper indicate that the effect of breaks in the walls at current modes is not detectable (i.e. is well within experimental error). The invariance of the window Q (Q_w) has been checked to better than 5 per cent.

It has been found that the Q of a copper cavity, whose surface has been finely machined with a carboloy tool, increases by over 30 per cent upon annealing in a hydrogen atmosphere. The annealed cavity had a Q only 6 per cent lower than that expected from the d-c conductivity.

An electrolytic polishing cell is being set up to investigate the influence of a finer surface finish. Also, subsequent cavities of copper will be made from vacuum copper instead of from just OFHC copper.

The best data thus far indicate that the fractional change in Q of a copper cavity from 300°K to 4.2°K is the same as that observed by A. B. Pippard[1], if it is assumed that the appropriate frequency corrections are not in error.

Measurements of surface conductivity of metals at 10,000 Mc/sec and at low temperatures were started at the beginning of this quarterly period. As a resonator for measurements of Q's a quarter-wavelength section of a two-wire line was chosen (about 8.4 mm long, 0.75 mm apart, wire 0.62-mm diameter). The wire is prepared by casting the metal (tin, lead) in vacuo in a glass capillary. Then it is bent in a U-shape, annealed, and mounted in a cylindrical shield of a diameter below cut-off for the lowest mode. The resonator is coupled to the standard waveguide through an orifice in the shorting end plate.

The measurement of Q is performed in a standard way (see RLE Technical Report Nos. 7 and 21) from the width of a resonance curve or from the VSWR at resonance. It was found by previous measurments that the window Q remains constant within the limits of precision during the change of unloaded Q (Q_o) caused by cooling. The Q's can be determined with a precision of ± 5 per cent (mean from 10 experiments). One run has been made in the Collins cryostat with a tin resonator. Ten points on the Q_o-vs.-T curve were obtained. The ratio of Q_o (low temperature)/Q_o (room temperature) was 1.26 at 100°K, 2.57 at 55°K, and 6.80 at 10°K.

---

[1] A. B. Pippard, Proc. Roy Soc. A191, November 1947.

III. A. 4. Investigations of Second Sound in Liquid Helium II

Staff: Dr. J. R. Pellam

Upon the departure of Drs. Horvath and Desirant (guests at the Laboratory), the early program[1] to conduct second-sound measurements at extremely low temperatures using demagnetization was discontinued for the time being. It had become evident that too large a step had been attempted, and emphasis was shifted rather to perfecting techniques for second-sound measurements. In this direction the thermal pulse technique for second sound was developed and shown to have several inherent advantages over the standing-wave method employed by Peshkov[2] and Lane[3].

Pulse Method. Application of pulse methods to second sound was accomplished by generating heat pulses electrically within liquid He II and detecting the resultant "thermal wave" at a later instant of time upon arrival at a receiver (bolometer). In this manner the usual potentialities of the pulse method[4] were realized, plus additional features unique to the case of liquid helium.

That thermal pulses may be generated and propagated in He II, and then detected and presented on an oscilloscope in this manner constitute independent proof of the existence of second sound and of its wave characteristics. Samples of such second-sound pulses at various temperatures are shown in Fig. III-1, for which the transit distance between generator and receiver was fixed at 7.555 cm. The time sweep proceeds from the extreme left (where the d-c generating pulse arises through pickup within the gear) toward the right. Since the sweep commences simultaneously with the beginning of the videopulse, the location of the received signal is a measure of transit time, leading to velocity.

To facilitate taking large quantities of data rapidly, photographic methods were used throughout. By sufficiently reducing the beam intensity of the A/R Radar Range Scope, the 10,000-yd. range markers alone appear, so that the trace is composed of markers. Subsequent counting of the number of these (each representing 61.1-μsec. delay) between the start of the generating pulse and the beginning of the received signal leads to wave velocity. Thus the shifting of the signal toward the left in Fig III-1 as temperature decreases illustrates the corresponding increased wave velocity.

The advantages of the pulse technique accrue mainly from its fundamental directness. Thus distance travelled per unit time is velocity, no recourse to resonant systems[2,3] or other complications being necessary.

---

1. Quarterly Progress Report, April 15, 1948, p. 21.
2. V. Peshkov, J. of Physics 10, 389 (1946); also ibid, 8, 381 (1944).
3. C. T. Lane, H. Fairbank, H. Schultz and W. Fairbank, Phys. Rev. 70, 431 (1946) and ibid 71, 600 (1947).
4. J. R. Pellam and J. K. Galt, J. Chem. Phys. 14, 608 (1946)

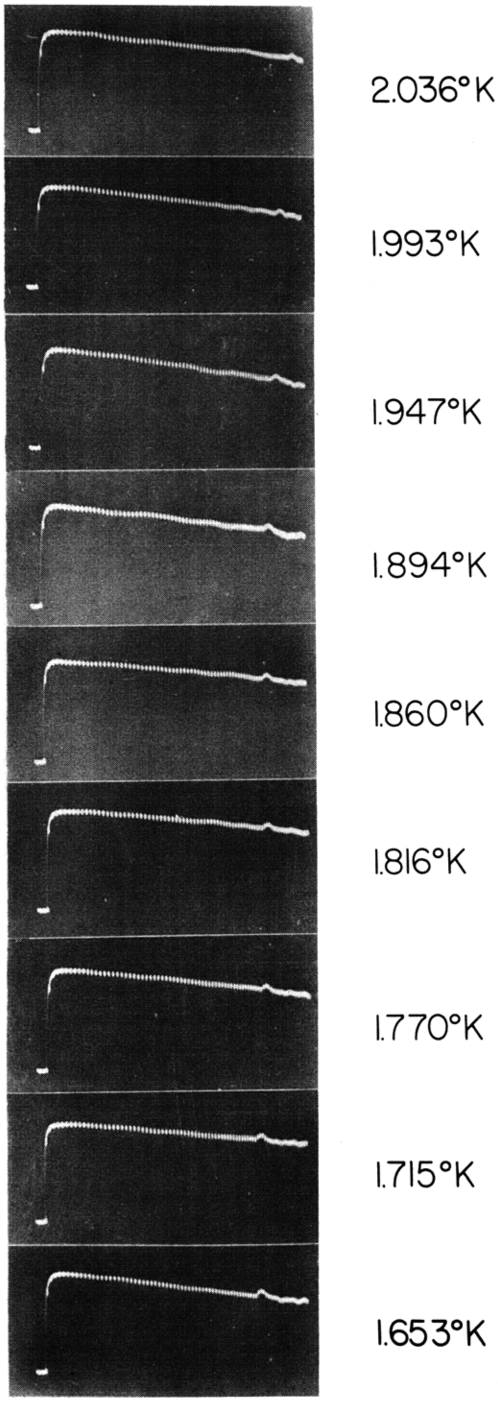

Fig. III-1. Second-sound pulses at various temperatures for fixed transmitter-receiver distance (7.555 cm) (generating pulse appears at left through pickup within gear).

Investigation showed that the starting time of the received signal is independent of both repetition rate (78 per second or greater) and pulse duration, so that for these measurements no distinction between group and phase velocity need be retained.

The direct-reading feature of this method eliminates the necessity for maintaining accurate temperature control during a series of measurements as required for standing-wave methods. Photographic techniques require temperature stability only during approximately one second, so that rapid readings are made possible. For the velocity measurements just below the λ-point where the velocity depends critically upon temperature (see Fig III-4), maintaining the positions of the signal constant on the screen actually constituted the best temperature control. A further consequence of instantaneous readings is the opportunity for extending measurements to lower wave velocities (i.e. temperatures nearer the λ-point) than attained by standing-wave methods.[1] Thus wave velocities of under 3m/sec have been measured, and signals observed corresponding to only about 1.5 m/sec.

<u>Attenuation Measurements</u>. The isolation of the second sound in discrete packets of energy (pulses) makes possible attenuation measurements in the same general manner as for ultrasonic pulses in liquids.[2] The pulses travel down a cylindrical glass guide of uniform cross section, so that any loss of intensity is due to liquid absorption. Thus if the receiver is moved with respect to the transmitter, the variation in signal strength leads to attenuation of second sound in traversing liquid He II.

Photographic recording is especially applicable to such attenuation measurements. A motion picture is taken of the screen as the receiver is moved with respect to the transmitter so that the decrease in signal strength with increased transit distance may be recorded rapidly for later analysis (knowledge of wave velocity gives transmitter-receiver distance at all times).

<u>Extreme Low-Temperature Measurements</u>. In previous research[3,4] on the temperature dependence of second-sound velocity, the low-temperature limit had been set by the heat input in generating the standing wave. For the present method not only may the liquid be heated only during the exposure of the film but also the average power (due to the intermittent characteristics) is itself relatively low.

<u>Application to Interaction or Coupling Effects</u>. The pulse method is particularly suited for studying interactions between second sound and other

---

1. V. Peshkov, loc. cit.
2. J. R. Pellam and J. K. Galt, loc. cit.
3. V. Peshkov, loc. cit.
4. C. T. Lane, H. Fairbank, H. Schultz and W. Fairbank, loc. cit.

types of wave propagation. For example, the coupling efficiency in the "Yale effect", conversion of second sound to classical sound in the vapor occuring at the liquid-vapor interface, may be analyzed by recording the signal on motion picture film as the receiver is moved in or out of the He II. Relative signal strengths lead to coupling factors (ordinary sound is detected in the vapor since it produces temperature fluctuations; i.e. for vapor $\gamma > 1$).

Also any inherent delay occurring during such an interchange at the surface should be evidenced by plotting delay time versus transmitter-receiver distance. Analysis of considerable data relative to these effects is now in progress.

Because of the great difference between the wave velocities of first and second sound (10 to 1 ratio, or greater) conversion between second and first sound within the liquid He II may be investigated (see results).

Equipment.

a) Electrical.

The block diagram is shown in Fig. III-2 and the timing sequence is as follows. Triggers from the A/R Range Scope simultaneously start the sweep and activate the multivibrator. Video pulses from the multivibrator (variable pulse length up to hundreds of μsec and variable magnitude up to roughly 50 volts) travel to the generator (a resistor), accordingly producing thermal pulses within the liquid. The receiving element (resistance a function of temperature) carries a constant 4-ma d-c current so that thermal fluctuations due to the second sound result in voltage pulses which are sent to an audio amplifier. These amplified signals are then presented on the vertical plates of the scope. Because of the extremely low wave velocity of second sound (20 m/sec or less), the 45000-μsec sweep is used and the minimum repetition rate of 78 per second.

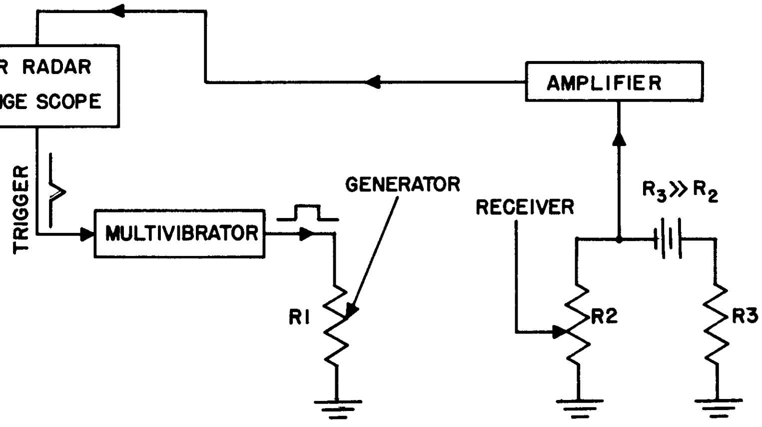

Fig. III-2. Block diagram.

b) Low-Temperature Apparatus.

A sectional view of the low-temperature gear with variable transmitter-receiver distance (in earlier gear this distance was fixed) is given in Fig. III-3. The apparatus rests in a dewar (A) containing liquid helium which, in turn rests within an outer dewar (B) containing liquid nitrogen. The video pulses from the multivibrator are fed down the small co-axial line (C) to the generator of second sound (E). This generator consists of a disk of resistance strip[1] (carbon layer on plastic base) of 800 ohms per square. The voltage pulse is fed to the center terminal (F) of this disk, the resultant current then flowing radially to the circumference which is grounded. Firm carbon-to-metal contacts are assured at both the center and edge by means of silver paste electrodes.

The second-sound pulse is constrained to travel within the glass tube (G) within which, in turn, rides the receiving element (H). This receiver is identical to the transmitter in that it also consists of a carbon layer disk. Here, however, advantage is taken of the temperature dependence of resistance of the carbon layer. (Because of the complete top-to-bottom symmetry in this respect, the role of the transmitter and receiver may be interchanged; when performing as a generator of second sound, the resistance strip is employed simply as a convenient resistor).

The center conductor (leading from the center of the receiver disk) carries the resultant pulses to the amplifier, passing through a glass bead vacuum seal (I) mounted within the movable tube (J). This brass tube (J) rides in a brass bearing (K) as a lower guide and supports the thin copper-nickel tube (L) to which the receiving element (H) is attached. The upper end of (J) screws into the brass cylinder (M) which in turn rides within a bracket (N) and acts as the upper support; the shielding of the coaxial line (O) leading from the gear is squeezed between the upper end of tube (J) and the cylinder (M).

The vertical position of the receiving element is read from the centimeter scale (and vernier) (P) and may be clamped in position by means of bracket (N). The entire system is maintained vacuum-tight by the crude rubber seal (R) which fits about the tube (J) and is attached to the cap (S) by means of a short tube (T). The system as a whole is tight enough to hold a half-millimeter vacuum for several minutes, ample for the helium vapor pressure range covered.

Results.

a) Velocity Measurements in Temperature Range from 1.54°K to the λ-point.

Figure III-4 shows the results of a large number of individual measurements (several hundred photographs have been taken) of wave velocity

---

[1] H. A. Fairbank and C. T. Lane, Rev. Sci. Inst. 18, 525 (1947).

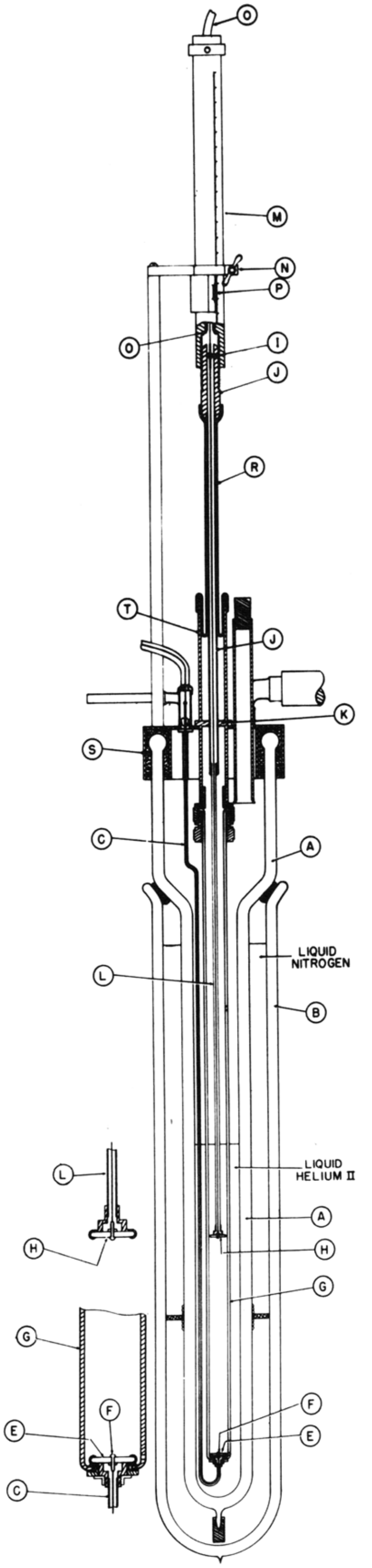

Fig. III-3. Gear with variable transmitter receiver distance.

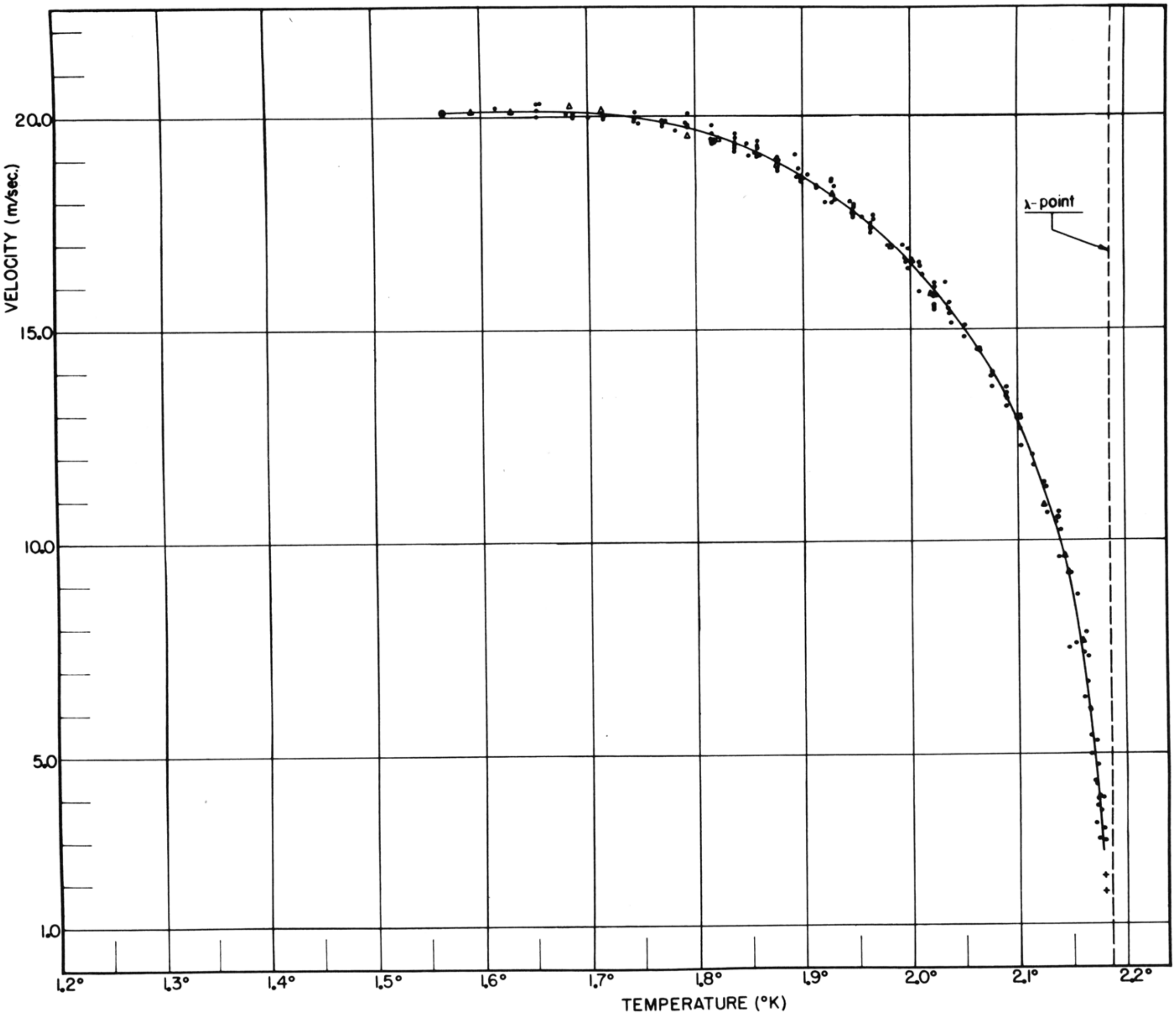

Fig. III-4. Second-sound wave velocity vs. temperature.

as a function of temperature. The circles (or dots) indicate velocities computed from the known transmitter-receiver separation and the measured delay time. The double circles were obtained by moving the receiving element by known increments and determining the resultant change in delay time. That the two methods give mutually consistent results indicates that there is no delay time involved in the formation of the second-sound pulse upon arrival of the video electrical pulse.

Individual points are shown in Fig. III-4 so that the amount of scatter may be observed. The majority of the measurements lie within a band of one per cent width. Actually, the method is capable of considerably greater accuracy than is suggested by this figure, where all velocity determinations have been plotted. During the course of the measurements, the procedures were refined to the point where markedly less scatter occured. For example, the velocity values obtained from a final run (with an especially large transmitter-receiver separation) are plotted as triangles in Fig. III-4 and show a greater tendency than the average to cluster about the solid line which represents the most probable value. The results are in close agreement with both the measurements of Peshkov[1] and the predictions of Tisza[2].

b. <u>Attenuation Measurements in Same Temperature Range</u>.

Figure III-5 shows the dependence of attenuation of second sound and temperature. The "temperature attenuation coefficient" α for second sound, defined by the equation,

$$T = T_0 e^{-\alpha x} , \qquad (1)$$

is plotted in reciprocal centimeters. Due to the inherent nature of the measurements there is considerable scatter, but a very definite trend is evident. Just below the λ-point second sound encounters very high attenuation ($\alpha = 3.5$ cm^{-1}), but as temperature decreases, the attenuation falls off rapidly until by 2.0°K α is roughly 0.1 cm^{-1}. Finally, for temperatures of 1.7°K and below, no measurable attenuation is in evidence.

---

[1] V. Peshkov, loc. cit.

[2] L. Tisza, Phys. Rev., <u>72</u>, 838 (1947).

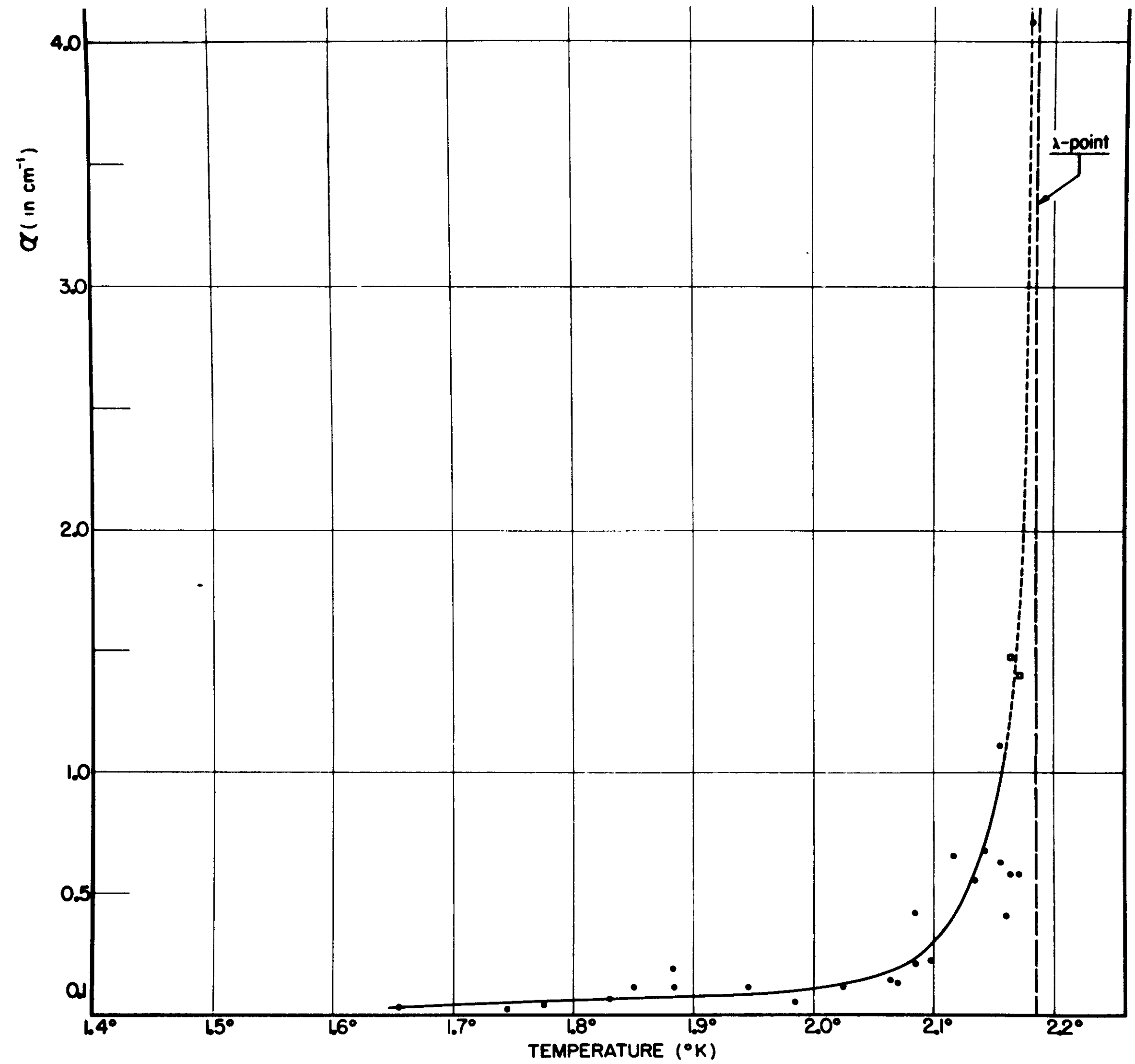

Fig. III-5. Variation of attenuation of second sound with temperature.

It is pointed out that, video pulses are employed throughout, the frequency factor (i.e. corresponding to the ω^2 for ultrasonics) is left undetermined. However, the dependence of α on temperature (i.e. relative values) is indicated, and consideration of the pulse spectrum might give more information.

c) Interaction or Coupling Effects.

Yale Effect: As previously stated, analysis of a large quantity of photographic data for the Yale effect is under way.

Overdriven Second Sound: By subsituting a classical microphone (vibration) for the second-sound element, presence of second sound is no longer directly evident. However, it has been found that, still using the thermal method of excitation, pulses are obtained via such a microphone and the delay times are such as to associate them definitely with first sound. A sample photograph of this is given in Fig. III-6.

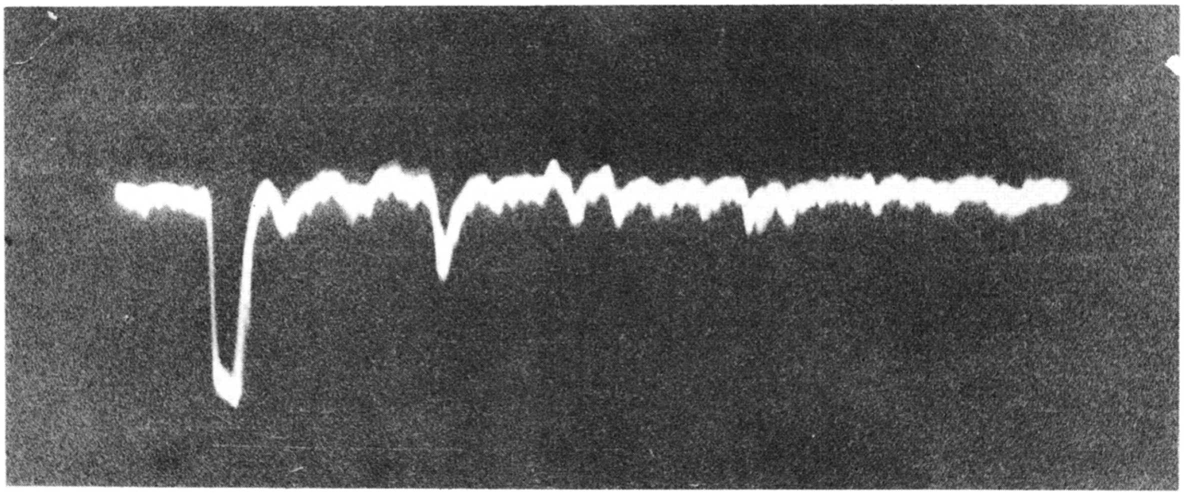

Fig. III-6. Presence of first sound detected by vibration microphone. (Note short time delay due to higher velocity.)

It is also observed that this effect occurs only when the input power exceeds certain critical lower limits. This may be an effect similar to the breakdown of superfluid flow through capillaries observed by Kapitza,[1] and predicted by Peshkov[2] for second sound. That is, by sufficiently overdriving the liquid helium with second sound, turbulent effects may be introduced into the "internal convection".

<u>Extension to Extreme Low-Temperature Range</u>. Present effort is being directed primarily toward extending the velocity measurements to lower temperatures than previously attained by Peshkov[3] (1.15°K). This is of primary interest from theoretical considerations.

New gear designed for this purpose is now undergoing tests. In order to enable keeping gear immersed for long periods of time in liquid helium, very long dewars (32 in.) were constructed, see Fig III-7. The inner dewar (A), containing the liquid helium, is designed to retain up to a two-foot depth of liquid which will be pumped sufficiently to maintain it at temperatures just below the λ-point (perhaps at about 2°K).

Suspended within this inner glass dewar is a metal container (B) within which rests an inner capsule within which the temperatures below 1°K are to be produced. Liquid helium will be obtained within this inner

---

[1] P. Kapitza, J. of Physics, U.S.S.R., <u>5</u>, 59 (1941).
[2] V. Peshkov, lov. cit.
[3] V. Peshkov, loc. cit.

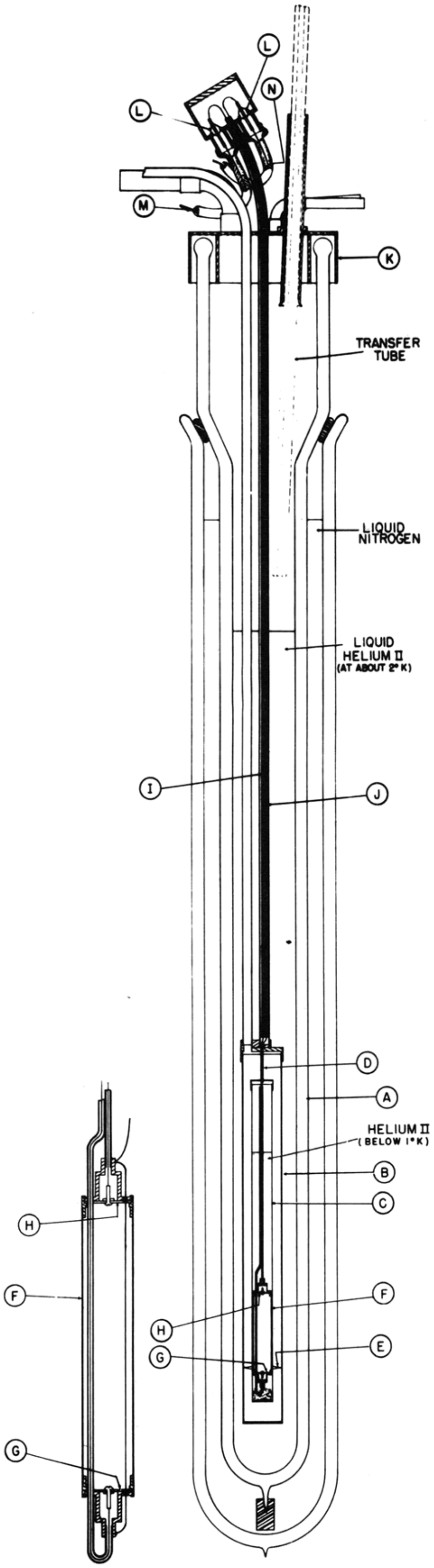

Fig. III-7. Gear for extending velocity measurements below 1°K.

container (C) by condensing vapor under slight pressure through the narrow neck (D) and using a slight pressure of helium gas within the space between (B) and (C) as a transfer gas. Upon condensing sufficient liquid into (C), the intermediate space between the two metal containers will be evacuated, and the measurement chamber will thus be thermally isolated. Heat inflow may then occur mechanically only via the narrow tube (D) or through the three phonograph needles (E) employed to prevent the measurement chamber from moving horizontally, or electrically during the pulsing and measurement of second-sound velocity.

Within chamber (C) is placed a second-sound cell (F) similar electrically to the arrangement already described, but with fixed transmitter-receiver distance, roughly two inches. Leads from the transmitter (G) and the receiver (H) travel via narrow tubing to the narrow neck (D), through which they must pass unshielded; however, intercoupling between the two systems is not serious due to the time delay characteristics of the method--i.e. pickup effects have occured "long" before the second pulse reached the receiver and is to be detected. Above this narrow neck, the leads again enter shielding tubes (I) and (J) through which they are conducted to the upper portion (K) of the apparatus, where vacuum seals (L) (glass beads) allow connection to outside coaxial lines (M) and (N).

As with all of the foregoing, temperature will be determined from vapor-pressure measurements with a McLeod gauge. In order to avoid possibility of pressure variations in the line, due to possible turbulence within the constriction (D), extreme low temperatures will be reached and measurements taken during the warming process. Under these "static" conditions in the absence of pumping, no inaccuracies should be introduced.

5. Mechanical Excitation of Second Sound in Liquid Helium

Staff: Dr. J. R. Pellam

This experiment (for which gear at 1 Mc/sec has been ready for test for some time) has been set aside in order to complete the investigation of second sound using thermal excitation, (see Sec. III. A. 4). Until opportunity for testing occurs, this experiment is being suspended.

6. Theory of Liquid Helium

Staff: Professor L. Tisza
R. J. Harrison

A phenomenological theory of quantum liquids has been given in RLE Technical Report No. 39. Attempts are being made to give a quantum mech cal foundation to the above theory. The method of second quantization seems to be adequate for this purpose. Hereby the role of statistics (Bose-Einstein or Fermi-Dirac) is of importance. From the experimental point of view, this is borne out by recent observations on mixtures of the two helium isotopes, He^3 and He^4.

B. PROPERTIES OF MATTER AT ULTRASONIC FREQUENCIES

Staff: R. A. Rapuano

High Frequency Ultrasonics. Measurements of the attenuation of CS_2 and glycerine made with the modified tank, confirm the results discussed in the Quarterly Progress Report of April 15, 1948. A definite and reproducible deviation from the relation α/f^2 = const. has been recorded. As expected, the effect seems to be quite temperature-sensitive.

Cavity resonators for the transducer crystal have been constructed, one of which covers from 150 to 350 Mc/sec, the other from 700 Mc/sec to about 1100 Mc/sec. A new cavity is expected to fill in the region from 350 to 700 Mc/sec, thus making possible the measurement of attenuation in that region.

In order to examine the temperature dependence of absorption, a thermostat is under construction.

C. PHASE TRANSITIONS

Staff: Professor L. Tisza
M. J. Klein

The work discussed in the April 15, 1948 Progress Report is being continued. We are carrying out a new derivation of the formulas for the scattering of light by a fluid in the vicinity of its critical point. (These formulas were first derived by Ornstein and Zernike.)

We start from the usual representation of the state of the fluid by a canonical ensemble and then approximate this by a distribution function which is Gaussian in form and whose variables are deviations from the mean particle density in the small volume elements into which the volume is divided. From this Gaussian distribution we can rigorously derive a matrix equation, similar in form to the integral equation obtained heuristically by Ornstein and Zernike, which relates the correlation of fluctuations in different volume elements to the interaction between volume elements. At the critical point these correlations have an important effect and extend over large distances.

The equation will be solved approximately and the results used to discuss critical opalescence and other problems in phase transitions.

III. D . ULTRASONIC ABSORPTION IN LIQUIDS

Staff: R. Parshad

It has been suggested previously,[1] that the high ultrasonic absorption in liquids is due to the energy released in the polarization of electron-atmospheres produced under periodic compressions due to ultrasonic waves. This polarization energy is converted into interatomic vibrations, and finally dissipated in the form of heat.

In continuation of the above physical explanation, the following expression is obtained

$$\alpha \propto \frac{f^2}{v} \chi \; p^2 \; f\left(\frac{\partial E}{\partial V}\right) f(\nu).$$

α = the non-classical part of ultrasonic absorption
f = frequency of oscillation
v = sound-velocity
χ = compressibility
p = polarizability.

If the volume of the liquid is greater than the volume V_o, $f\left(\frac{\partial E}{\partial V}\right) = \frac{1}{\frac{\partial E}{\partial V}}$, corresponding to the maximum of $\frac{\partial E}{\partial V}$, and for a volume less than V_o, $f\left(\frac{\partial E}{\partial V}\right) = \frac{\partial E}{\partial V}$. $f(\nu)$ is a function of interatomic vigration frequency ν and has not as yet been calculated.

The above expression quantitatively represents the change of absorption of both normal and abnormal liquids with temperature and pressure.

---

[1] R. Parshad, Nature, 158, 874 (1946).