ULTRASONIC MEASUREMENTS IN METALLIC BERYLLIUM AT LOW TEMPERATURES

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INTRODUCTION

The field of electronics underwent a considerable advancement during the war resulting in both an increase of knowledge of electronic phenomena and the introduction of a large number of new practical applications. The most outstanding achievement during this period was the development and highly successful field operation of radar. Almost every field of scientific endeavor has gained new techniques and instruments because of these advances in electronics. One of these new techniques, made possible by electronic pulsing methods similar to those used in radar applications, is called the "Ultrasonic Pulse Method". This is a precision technique by which accurate measurements of the velocities of propagation of sound waves in solid, liquid and gaseous media can be measured, and by which some of the mechanical properties of materials can be determined. This new technique has made possible the experiments about which this thesis is written.

The term "ultrasonics" is used to denote those frequencies of sound waves which are above the limits of the audible range; that is, above 20,000 vibrations per second. There are several methods of producing ultrasonic waves in the material in which one wishes to determine the velocity of sound and many of these methods are described by Bergmann in his book "Ultrasonics". The most widely
used method of producing sound for velocity measurements in solids is that of utilizing the electrostriction property of piezoelectric quartz. Crystalline quartz plates, when used as generators and detectors of sound energy, are called electromechanical transducers. It is convenient that either longitudinal or transverse waves may be produced by using X-cut or Y-cut quartz plates. The major tools of ultrasonics that use quartz as the electromechanical transducer are the acoustic interferometer method, the optical diffraction method and the new technique, the ultrasonic pulse method.

Ultrasonic pulse methods were in use as early as 1942, as a time storage device and as delay lines to store and hold radar signals for several milliseconds. Kittel reports early workers in ultrasonic pulse techniques as W. Shockley of Bell Telephone Laboratories, H. Grayson of the British Telecommunications Research Establishment and F. Kruse of Telefunken in Germany, as well as the Radiation Laboratory at Massachusetts Institute of Technology, which was very active in the field.

Some of the first workers who used the new technique to study velocity and absorption of sound and mechanical properties of matter were, beginning in 1945 with Arenburg; in 1946, Gefola, Droz, Frankel, Jones, Maslach and Teeter; in 1946 also were Pellam and Galt; and in 1947, Rapuano.
In the literature prior to about 1945 there are a large number of papers reporting the mechanical properties of solids as determined by the acoustic interferometer methods. Most of these papers have reported work in the room temperature and high temperature ranges, while relatively few report measurements made in the low temperature range. Balamuth, in 1934, obtained the elastic moduli of rock salt by a special form of the acoustic interferometer method from 80° K to 300° K. In 1936, P. C. Rose using Balamuth's method, determined the adiabatic and isothermal elastic constants of rock salt from 270° K to 80° K. Ultrasonic measurements on several other alkali halide solids and on several metals have been determined as low as 80° K by the acoustic interferometer method.

In 1947, Huntington obtained the elastic constants of LiF, NaCl, KBr, and KI, at room temperature by the ultrasonic pulse method. His are perhaps the first measurements of the mechanical properties of these alkali halides by the new technique. Galt, in 1948, measured the principle elastic constant $C_{11}$ in KBr single crystals down to 4° K using the ultrasonic pulse method. His sample was placed in the experimental chamber of the M.I.T. Collins-type helium liquefier, so that measurements could be made while the low temperatures were being produced. So far as is known, Galt's determinations of the elastic constant $C_{11}$ for KBr are the only measurements on solids that have, so far,
been carried with accuracy to such low temperature using ultrasonic methods.

Prior to the measurements on beryllium described in this thesis, perhaps the highest velocity that had been measured was reported by Theide in 1941. He found the velocity in a German material "Degussit" (aluminum oxide) to be about 9,600 meters per second. The measurements on beryllium indicate a velocity of 12,570 meters per second, at 270° K increasing slightly to about 12,700 meters per second, as the temperature is lowered to about 150° K. Although the velocity in diamond has been computed, from the static measured values of the elastic moduli, to be higher than this velocity in beryllium, it appears that these direct sound velocities for beryllium are the highest that have been measured to date.

The literature contains very little information concerning the mechanical properties of beryllium. Bridgman obtained a value of $8.85 \times 10^{-13}$ cm$^2$ dyne$^{-1}$ for the isothermal compressibility of beryllium, at 30° C and 75° C. No other information could be found concerning the elastic moduli or elastic constants.

The specific heat of beryllium has been measured by Simon and Critchley who observed an anomaly at 12° K (Figure 1). This anomaly or hump is about twice the magnitude of the specific heat at 12° K that would be obtained if the value at about 18° K was extrapolated down
to 0°K according to the Debye $T^3$ law. It was thought that this specific heat hump might possible be explained on the basis of a change in the lattice constants at that temperature. If this were the case, one should observe a change in the sound velocity provided this velocity could be measured accurately enough. Simon and Gritescu attribute the specific heat hump to electronic causes. This may actually be the case, but one is inclined at first not to think so in view of the resistivity curve, as obtained by Squire,\textsuperscript{10} which indicates no peculiarity in the neighborhood of 12°K (Figure 2). However, this resistivity curve in itself is unusual in that it does not approach zero at the absolute zero as do most other metals. The magnitude of an expected velocity change, if such an anomaly in the specific heat is due to a lattice change, is difficult to determine but it is expected that such a change might be small enough as to lie within the experimental error. If this is the case, then the results of the velocity measurements would not allow one to conclude whether the anomaly in the specific heat is due to electronic causes or due to a change in lattice constants.

The experimental difficulties in making ultrasonic measurements on solids, increase greatly as one goes to lower temperatures. This is perhaps the reason why so little data has been obtained at low temperatures. In accurate work on solids the piezoelectric transducer should be rigidly
Figure 1: Low Temperature Heat in Peryllium.

Figure 2: Resistivity of Peryllium.
bound to one face of the solid in which the ultrasonic velocity measurements are being made. In general, organic materials, such as vaseline, ceresin wax, salol and ordinary stopcock grease may be used as cements or binding agents at room temperature and perhaps as low as about 120° K. These binding agents are applied as a thin sound conducting layer between the quartz crystal and the smooth surface of the solid. This makes it possible to generate longitudinal or transverse waves in the solid, depending on the type of quartz plate used as a transducer. However, as one goes to lower temperatures, the different rates of contraction of quartz, solid and cement introduce strains that may break the quartz loose from the solid or even shear the solid. Galt encountered this difficulty in his measurements on KBr. The methods by which some of these difficulties have been overcome, in the measurements on beryllium, are described in a later section.

THE ULTRASONIC PULSE METHOD

The operating principle of the ultrasonic pulse method is best described by reference to Figure 3. A crystal controlled timing circuit in the Du Mont oscilloscope starts the oscilloscope time base sweep and simultaneously sends a trigger pulse to the R. F. Pulsed Oscillator. The radio frequency pulse formed by the oscillator is amplified
Figure 2. Functional block diagram of ultrasonic pulse method.
and passes through the impedance matching network to the quartz transducer, which introduces a pulsed sound wave into the solid. This sound wave is propagated through the solid to the bottom face where it is reflected and then returns to the transducer forming a delayed electrical pulse. Since the radio frequency generating circuit is off when the echo signal arrives, very little leakage loss occurs and most of the energy travels through the attenuator to the receiver.

Both triggering and time measurements are accomplished by means of crystal-controlled circuits in the A/R Scope. This feature is partly illustrated in Figure 4. Figure 4a is the trigger which is sent out simultaneously with the start of the sweep (Figure 4b). The trigger starts the Pulse Former whose output (Figure 4c) starts the Pulsed Oscillator. The Pulsed Oscillator generates the signal (Figure 4d) which is amplified (Figure 4e) and then produces the sound pulse as described above. Figure 4f shows the echos representing reflected sound waves as displayed on the oscilloscope. A delayed sweep circuit in the oscilloscope is used to measure the timing on the leading edge of each echo signal. This feature of the A/R Scope permits an accuracy of 0.02 microseconds. The next section describes in some detail the operations of the electronic circuits which the reader may omit if desired.
Figure 4. Waveforms in the "Ultrasonic Pulse Method."
CIRCUIT DETAILS

In order to determine the time difference between successive pulses with accuracy it is necessary to measure the time of occurrence of the leading edge of each pulse. It is possible to measure the time of occurrence of each pulse with an accuracy of ± 0.02 microseconds. The feature of the DuMont A/R Scope which makes such an accurate measure possible is briefly described. The sinusoidal output of a 100 kc/sec. crystal controlled oscillator is distorted to produce a continuous chain of short one-half microsecond pulses spaced by exactly 10 microseconds. A "Divider" circuit is adjusted to select just one of these pulses once each 1/100 to 1/1000 of a second. This "Divider" circuit allows a choice of a working cycle rate or "pulse recurrence rate" of 100 to 1000 per second, the usual rate being about 300 per second. The selected pulse is then used to synchronize all oscilloscope and external trigger operations for one working cycle. All of the short pulses following the one selected by the divider circuit may be used as markers for time calibration purposes, since they are spaced by exactly 10 microseconds.

The selected pulse, as illustrated in Figure 5a, is used to trigger a one-shot multivibrator which produces a negative going square wave, (Figure 5b) of 100 (or 1000) microseconds duration. This square wave form is fed to the
input of tube V₂ (Figure 5). Tube V₂ is normally conducting heavily through diode V₁ and R₂ because of the positive grid voltage obtained from positive 250 volts and the grid current (drop over R₁) across R₁. The square wave (5b) voltage cuts off the current through V₂ for 100 microseconds. During this period the condenser C₁ charges linearly through diode V₁ and resistor R₂. Condenser C₁ charges linearly instead of exponentially because V₁ is a constant current diode. The resulting waveform is the linear sawtooth voltage as in Figure 5c. The cathode of diode V₃, across which the sawtooth voltage is applied, is set at any desired potential by positioning the movable contact of the potentiometer P. Only that portion of the sawtooth voltage which exceeds the cathode potential can cause diode V₃ to conduct. This is illustrated by the point T on the time axis of Figures 5c, 5d, 5e, 5f, and 5g. The output of the diode V₃ is then of the form shown in 5d. The voltage waveform 5d is then amplified by later stages, (Figure 5e) and then differentiated by a short time constant circuit resulting in the peaked waveform Figure 5f. This voltage is then used to trigger a time base circuit which produces the sawtooth voltage Figure 5g. This sawtooth voltage may be either 4, 10, or 25 microseconds duration and is applied across the horizontal deflecting plates of the oscilloscope to provide the sweep.

The potentiometer P (Figure 5) has a 10 turn
Figure 5. Sweep Delay Circuit and waveforms.
Helical winding and the adjustable tap is positioned by a calibrated micrometer "Sweep Delay Dial" having 3600 degrees of rotation. On the 100 microsecond scale the time lapsed between the starting time, say $t = 0$, of waveforms (5b) and (5c) and until the beginning of the sawtooth voltage (5g) at time $t = T$, may then be read directly from the Sweep Delay Dial in microseconds to an accuracy of ± 0.02 microseconds. (On the 1000 microsecond sweep scale the accuracy is ± 0.2 microseconds.) The sawtooth sweep voltage (5g) is of the proper amplitude to cause the time base trace to cover the full four inch width of the cathode ray tube face on either the 4, 10 or 25 microsecond scales. When the Sweep Delay circuits are not used, the oscilloscope trace may be set for either 100 or 1000 microseconds as shown in Figure 4f. The above brief explanation shows how it is possible to obtain readings of the time of occurrence of the leading edge of any pulse displayed on the cathode ray tube by positioning the potentiometer with the "Sweep Delay Dial" until the leading edge of the pulse is at the left edge of the oscilloscope trace. High accuracy is obtained because the careful design of the charging circuit, of which Figure 5 is a simplification, makes possible the extremely linear sawtooth voltage of Figure 5c, and because of the precision design of the helical potentiometer.

Small errors in the readings of the occurrence time of a displayed pulse may occur due to non-linearity of the
sawtooth waveform (Figure 5c) or due to non-linear portions of the helical potentiometer. Errors due to these causes are always very small and adjustment controls for minimizing these errors are incorporated in the A/R Scope. The adjustments are made with the marker pulses, which are generated by the 100 kc/sec crystal controlled oscillator and associated circuits, displayed on the oscilloscope.

Since these pulses are exactly 10 microseconds apart, the error of the "Sweep Delay Dial" readings may be determined. After proper adjustment the dial readings should not differ from the true time values as indicated by the marker pulses, by more than 0.1 microseconds. One may then make a calibration correction table with the 10, 20, 30 etc., microsecond intervals, as indicated by the markers, in one column and the "Sweep Delay Dial" readings in a corresponding column. The readings on any displayed sound pulses may then be corrected by reference to this table.

The DuMont A/R Scope is equipped for synchronizing, displaying and measuring the ultrasonic pulses, as has just been described. The operations of the additional electronic components, as shown in block diagram Figure 3, are now described. The Pulse Former, Radio Frequency Oscillator and Amplifier were built on one chassis from stock radio parts; and the schematic for the combination is shown in Figure 6. The Broad-band Receiver schematic is shown in Figure 7. This receiver was built around a war surplus radar set
intermediate-frequency amplifier which was originally designed for 30 Mc/sec and had to be redesigned for 10 Mc/sec. Two very stable electronically regulated power supplies were built for these two units.

The operation of the Pulse Former is that of the usual one-shot multivibrator as may be seen by reference to Figure 6. Triode V₁ normally conducts heavily due to the positive bias on its grid obtained from the circuit R₁, R₂, and R₄ (and R₃ for long pulses). Triode V₂ is normally cut off because of the negative grid bias obtained by raising the cathode to a positive potential by the circuit R₇ and R₉. The negative going one microsecond pulse from the A/R Scope is passed through coaxial cable to the Type H coaxial connector N₁. This pulse then cuts off V₁ causing the plate to rise to a higher potential and thus applying a positive pulse through C₂₀ to the grid of V₂. Triode V₂ then conducts through R₉ providing the cathode follower output at N₂ which is a positive going pulse as shown in Figure 4c. Normally C₂₁ has a negative charge on the V₁ grid side because the plate of V₂ is at a higher positive potential than the tap on the potentiometer R₂. When V₁ is cut off by the one microsecond pulse and V₂ goes conducting the grid of V₁ stays negative until the charge on C₂₁ leaks off through the conducting V₂ and R₂ and R₃. The time required for the charge of C₂₁ to leak off to a value such that the grid potential of V₁ is just
Figure 6. Pulse Former, Pulsed Oscillator and Amplifier.
above the cut-off value and for $V_1$ to again conduct, is determined by the setting of $R_2$. With the switch SW on "pulse width long", an output pulse of 8 to 40 microseconds may be obtained at $N_2$. On "pulse width short" the output pulse may be varied by $R_2$ from 1 to 10 microseconds.

The radio frequency circuit operation is as follows. The positive pulse at $N_2$ is applied to the grid of $V_3$ which is normally cut off. The output of $V_5$ is a negative going pulse which is applied to the grid of $V_4$. Triodes $V_4$ and $V_5$ are normally conducting heavily through the inductance $L_1$. When the negative pulse from $V_3$ cuts off $V_4$, the steady current in $L_1$ is interrupted causing the $L_1C_{10}$ circuit to ring or oscillate. The frequency of this oscillation is set at 10 Mc/sec by adjusting the variable condenser $C_{10}$. The oscillation is sustained for long pulses because the $V_5$ cathode tap on $L_1$ supplies the necessary feedback. As soon as the negative pulse applied to the grid of $V_4$ is over, $V_4$ again conducts and the oscillations of the LC circuit cease. The radio frequency pulse is amplified by the buffer stage $V_6$ and further amplified by $V_7$. The coupling coil $L_4$ provides the low impedance output (about 50 ohms) which is taken off at $N_2$.

The receiver (Figure 7) was originally a 30 Mc/sec. intermediate frequency amplifier having a 2 Mc/sec. bandwidth. The coils $L_1$ to $L_6$ had to be rewound to tune to 10 Mc/sec. This was accomplished with the aid of a Boonton
Figure 7. 10 Mc/sec. Receiver with 2 Mc/sec. Bandwidth.
Q Meter and final alignment accomplished with the aid of a General Radio Company signal generator. Alternate stages were peaked at frequencies on either side of 10 Mc/sec, so that the overall signal voltage output at 9 and 11 Mc/sec. was about 70% of the output at 10 Mc/sec. This is the usual criteria for a 2 Mc/sec bandwidth. With a bandwidth of 2 Mc/sec a one microsecond radio pulse may be passed without distortion of the pulse shape. The ultrasonic signals generated at the quartz were applied at the Type N coaxial connection $N_1$ and the output from the video amplifier was taken off at $N_2$. The regulated power supply and the gain control circuits were built on the same chassis. Referring to Figure 8 it is seen that when the potentiometer $R_{26}$ is varied, from one limit to the other, a variable grid bias ranging from 105 volts negative to 105 volts positive is impressed on $V_7$. This varies the $V_7$ conduction current from zero to a value which in turn varies the cathode potential from zero to 100 volts. The plate voltage of stages $V_1$, $V_2$ and $V_3$ is then changed by this circuit and gain control is accomplished.

**LOW TEMPERATURE APPARATUS**

The beryllium specimen holder, a cross section view of which is shown in Figure 8, was designed so that low temperature velocity measurements could be made with this apparatus in the experimental chamber of the Collins.
Heidum Cryostat as well as in an external Dewar flask. Referring to Figure 3, the beryllium solid specimen is held in a vertical position by four phosphor bronze springs $S_5$, and a spring $S_2$ pushing up on the brass plate $P_5$. In the space $D$, between this brass plate and the bottom of the beryllium specimen, a layer of paper and cotton is placed for the purpose of sound insulation. Such a layer absorbs only a negligible amount of the sound energy incident on the bottom face of the beryllium sample and does not affect the velocity measurements or attenuate the sound pulse appreciably.

The quartz crystal transducer $Q$ as shown in Figure 3 is rigidly affixed to the beryllium specimen. A thin layer of gold is evaporated on both faces of the quartz plate, and a non-conducting ring is etched out of one face. External contact is then made to the inner circular gold electrode of the quartz by the central contact on the plunger $P$ and contact to the outer gold ring electrode is made by the outer spring contact $S_1$. These contacts make up the concentric contactor as shown in Figure 3. The inner contact is a polished disk on the end of plunger $P$ and is free to move vertically in the well of textolite insulating material $W$. A helical spring in the well $W$ pushes the plunger down lightly so as to make good electrical contact. The outer contact is made of several concave circular springs fixed together so that the spring arrangement $S_1$ pushes down
Figure 8: Crosssection View of the Low Temperature Specimen Holder.
lightly on the outer gold ring electrode of the quartz. The concentric contactor is adjusted so that there is very little excess pressure exerted on the beryllium.

The radio frequency pulses from the matching network are fed down a coaxial cable to the quartz contacts as shown. This cable runs down the stainless steel tube \( T_1 \) and is waxed in at the top plate \( P_1 \) so as to make the system vacuum tight. The two leads \( L_1 \) and \( L_2 \) are connected to the central and outer conductor of the coaxial cable as shown.

Temperature measurements in the \( 80 \)°K to \( 300 \)°K range are made with a copper-constantan thermocouple \( C \). The leads to this thermocouple are taken out through the stainless steel tube \( T_5 \). A vapor pressure thermometer, consisting of the vapor pressure bulb \( V \) and the stainless steel capillary \( T_4 \), which leads to an external mercury manometer, is used to measure temperature in the hydrogen and helium vapor pressure ranges. A constant volume thermometer (not shown) in the Collins' Cryostat gives the temperature from 4° K to 80° K.

The upper plate \( P_1 \) fits over a rubber O-ring gasket at the top of the experimental chamber of the Collins Cryostat where the plate \( P_1 \) is bolted down to make an air-tight fit so that no helium can leak out. The bottom of the apparatus is 51 inches from the top plate \( P_1 \) and when in place in the experimental chamber the specimen is in the
lowest temperature region of the cryostat. A heavy-walled brass can is threaded into the flange on the plate \( P_2 \) and when this can is soldered to the plate \( P_2 \), the specimen holder may be evacuated through the large stainless steel tube \( T_2 \). Pumping this chamber to about one millimeter of mercury allows a very slow rate of cooling of the specimen.

**EXPERIMENTAL PROCEDURE**

For the velocity measurements in the range from 300° K down to 80° K the beryllium specimen was cooled by liquid air. The brass can was soldered to the specimen holder (Figure 2) and a large mouth Dewar flask was placed so as to surround the apparatus. The Dewar flask was then filled with liquid air and the measurements made while the sample slowly cooled. In this temperature range a calibrated copper-constantan thermocouple was used to measure the temperature. One thermocouple junction was placed at the middle of the beryllium sample and the other junction kept at 0° C in an ice filled Dewar flask. The thermocouple voltages were measured with a Leeds and Northrup Type K Potentiometer.

In the first attempts to carry the longitudinal velocity measurements to the low temperatures, the X-cut quartz crystal was cemented to the beryllium sample by first heating the sample to about 45° K and then applying a few drops of salol (methyl salicylate) on the top face of the
sample. The quartz crystal was then centered on the sample and held in place until the beryllium cooled below the salol melting point. The quartz then became firmly cemented to the beryllium and measurements could be made at room temperature. However, as soon as the temperature was lowered to $-30^\circ C$, the difference in the rates of contraction of the quartz, salol and the beryllium caused the quartz-to-beryllium bond to break and measurements were no longer possible. Several trials were made using salol as a cement but no measurements could be obtained below $-40^\circ C$.

Using a similar procedure, ordinary stopcock grease was next tried as a cement. This was much more successful than the salol, and considerable data on longitudinal waves was obtained in the temperature range from $270^\circ K$ down to $138^\circ K$. At $138^\circ K$ the stopcock grease bond broke so that measurements could not be made below that temperature. Figure 10 shows the average round trip travel time in the solid to be about $11.95$ microseconds at $140^\circ K$ and increasing to $12.25$ microseconds at room temperature. The deviation of the experimental points from the smoothed curve, in the neighborhood of $138^\circ K$, is not greater than $\pm 0.02$ microseconds.

When ordinary stopcock grease was used to cement the Y-cut quartz for the measurement of transverse velocities, measurements were obtained down to $112^\circ K$ before contraction
caused the bind to break. In the neighborhood of room
temperature, however, the stopcock grease becomes plastic
and will not transmit shear waves properly. Room tempera-
ture measurements were later taken using Ceresin wax for
the cement.

In order to obtain measurements in the temperature
region below 100° K, it appeared that some organic material
with a low melting point should be used as a cement. A
mixture of ether, isopentane and alcohol was suggested by
Dr. E. S. Lewis of the Rice Chemistry Department. This
mixture, in the ratios of 5 parts ether, 6 parts isopentane,
and 2 parts alcohol proved to be successful as a quartz-to-
beryllium binding agent down to 3° K. Lewis and Kasha,12
who gave the name EPA to this mixture, found that it
remained glassy, from about 90° K, where it begins to
solidify, down to 80° K. A few simple tests were made with
different amounts of ether, pentane and alcohol, and these
materials in the ratio by volume of 5, 6 and 2 appeared to
have the best characteristics as a binding agent.

This preparation could not be applied at room
temperature because it would evaporate before the tempera-
ture could be lowered. It was decided to first cool the
beryllium specimen to about 120° K and then apply the EPA
mixture. In doing this care had to be taken to prevent
moisture from condensing on the cold apparatus and the
beryllium. The procedure that finally developed was to cool
the specimen, with the outer brass can threaded into the plate P₂ of Figure 8, with the outer brass can surrounded by liquid air. When the temperature of the beryllium became 120° K, the liquid air Dewar flask was removed and the outer brass can was taken off the specimen holder. Dry nitrogen was forced down the central stainless steel tube P₂ to reduce the condensation of moisture on the cold specimen holder. A small amount of EPA liquid was dropped on the top face of the beryllium specimen, the quartz crystal was then properly placed and the concentric contactor was lowered onto the quartz. The outer can was again replaced and the liquid air Dewar flask brought back into place to continue the cooling.

Ultrasonic measurements were made as soon as the temperature of the specimen reached about 100° K, and these measurements were carried to 80° K using liquid air cooling. For measurements below 80° K the apparatus was transferred to the experimental chamber of the Collins Cryostat. Although moisture condensed on the cold apparatus during the transfer, the presence of the ice crystals on the beryllium specimen did not affect the low temperature measurements.

Following this procedure, measurements of the round-trip travel time of longitudinal waves were obtained down to 25° K and of transverse waves down to 5° K. In figure 10 the average round trip travel time for longitudinal waves in beryllium is plotted as a function of temperature. This
data is for the beryllium specimen of length 7.6022 centimeters at 0° C, so that the round trip distance is 15.2044 centimeters at 0° C.

**EXPERIMENTAL RESULTS**

The essential measurements were those of the average time required for an ultrasonic pulse to travel the round-trip distance through the beryllium solid. The experimental data recorded at a given temperature was the reading of the A/R Scope Sweep Delay Dial when the leading edge of each echo was brought to the left edge of the oscilloscope trace by turning the Sweep Delay Dial. A typical example of the recorded data for one of these points follows.

<table>
<thead>
<tr>
<th>Temp.</th>
<th>Echo Number</th>
<th>Sweep Delay Dial Reading</th>
<th>Correction</th>
<th>True Time On Leading Edge</th>
<th>Time Difference Microseconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>150°C</td>
<td>8</td>
<td>97.31</td>
<td>+ 0.05</td>
<td>97.36</td>
<td>12.06</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>85.30</td>
<td>+ 0.10</td>
<td>85.40</td>
<td>11.80</td>
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<tr>
<td></td>
<td>6</td>
<td>73.40</td>
<td>+ 0.10</td>
<td>73.50</td>
<td>12.00</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>61.50</td>
<td></td>
<td>61.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>49.58</td>
<td>-0.05</td>
<td>49.53</td>
<td>11.97</td>
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<td></td>
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<td>37.53</td>
<td>12.00</td>
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<td></td>
<td></td>
<td></td>
<td>Average 11.99</td>
</tr>
</tbody>
</table>
The average time difference value of 11.99 microseconds is plotted as an experimental point in Figure 10. The usual statistical methods of treating data cannot be used, for an examination of the last column and of the experimental nature of the measurements shows that this data is not random. Furthermore it is almost impossible to properly weight the various values because the too large or too small values occur between different echoes at different temperatures.

The pulse shape of each echo, as it appears on the oscilloscope is an important factor in deciding whether the reading obtained is a good representation of the proper travel time for that echo. Sound waves that reflect from the cylindrical walls of the sample or from some internal crystallite boundary may arrive at the quartz transducer just in time to interfere with the main sound pulse that has traveled vertically downward, reflected from the bottom face and returned to the quartz. Such interference may be destructive or constructive. It is possible for destructive interference to affect the leading edge or trailing edge of the sound pulse. In either case destructive interference could cause the leading edge to occur later than if the interference had not been present. It is not immediately obvious why this may be so, but if one recognizes the characteristics of the receiving circuit it becomes evident. Destructive interference with either the pulse leading edge
or trailing edge results in a narrower pulse to the receiver. Since the receiver has a bandwidth that will pass without distortion only the broader pulses, a narrow pulse will be distorted so that the leading edge does not have as steep a slope as the normal pulses. When such a pulse, combined with the normal noise in the circuits, is passed through an amplifier, the leading edge is no longer sharply defined and when displayed on the oscilloscope may appear late. Figure 9 is a typical example of destructive interference. This figure represents the oscilloscope picture for longitudinal waves at 25° K. All of the pulses had clean and sharp leading edges except the second and sixth echoes. The second echo was very weak while the third echo for the same gain setting was almost at saturation amplitude. The second echo appeared to indicate the presence of a scattered wave interfering with the leading edge and also lasting about 4 microseconds after the expected position of the trailing edge. The leading edge was almost obliterated and the reading on the leading edge was about 1 microsecond later than the expected value. Echo number six showed some interference with the leading edge for the reading was later than the expected value, while the eighth echo had a sharp and clean leading edge at about the right location. An accurate measure on the first and eighth echoes should give very nearly the true time difference for seven reflections. The amplitude of the second echo changed with the
Figure 9. Oscilloscope Picture for Longitudinal Waves at $23^\circ K_0$ showing destructive interference of the second echo. The third echo was almost at saturation amplitude.
temperature but the interference with its leading edge was present at all temperatures.

Constructive interference of scattered sound, with the leading edge of a pulse that has just arrived at the quartz, can produce a signal that is broader than the normal pulse and the leading edge may appear too early. Because of the complexity of the interference and scattering it is almost impossible to determine precisely the time of arrival of some of the pulses at the quartz. Errors due to such interference may be expected to be fairly small, since each pulse is always observed to within 0.1 or 0.2 microseconds of its proper location. An average taken over a sufficient number of these pulses reduces the error of observation to quite a small value. One might expect that for seven time differences, as is shown in the above table, that the average error would be about $\pm 0.05$ microseconds or less. This error added to the normal random error of reading of $\pm 0.02$ microseconds gives at most an error of $\pm 0.05$ microseconds, which corresponds to about 0.4 percent for the longitudinal waves. This conclusion is not very satisfying for it was hoped that the error would not be greater than one part in a thousand.

If the ultrasonic method were used at say, 20 Mc/sec or 50 Mc/sec instead of 10 Mc/sec, a narrower sound beam would be obtained and less scattering of the beam would result. Also at the higher frequencies a narrower pulse.
could be used and the uncertainty of the location of a reflected echo would be reduced.

Reference to Figures 10 and 11 shows that some of the points are as far as 0.04 microseconds from the smoothed curve. These deviations are considered as errors on the basis of the experimental difficulties just discussed and from the data points the following table of estimated errors is obtained.

**Longitudinal Waves**

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>Estimated Error (microseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20° K to 40° K</td>
<td>± 0.02</td>
</tr>
<tr>
<td>40° K to 80° K</td>
<td>± 0.04</td>
</tr>
<tr>
<td>80° K to 250° K</td>
<td>± 0.02</td>
</tr>
<tr>
<td>250° K to 310° K</td>
<td>± 0.03</td>
</tr>
</tbody>
</table>

**Transverse Waves**

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>Estimated Error (microseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3° K to 30° K</td>
<td>± 0.03</td>
</tr>
<tr>
<td>30° K to 80° K</td>
<td>± 0.04</td>
</tr>
<tr>
<td>80° K to 300° K</td>
<td>± 0.05</td>
</tr>
</tbody>
</table>

The length of the beryllium specimen was carefully measured at 28° C and found to be 7.6048 cm. On the basis of the linear coefficient of expansion as given in the Handbook of Chemistry and Physics of $12.3 \times 10^{-6}$ cm/deg/cm length, the round-trip travel distance as shown by the linear dotted curve in Figure 13 was obtained. It is well known that the coefficient of expansion approaches zero.
Figure 10. Average round-trip travel time for longitudinal waves.
Figure 11. Average round-trip travel time for transverse waves.
near the absolute zero, so that the use of the linear curve to obtain the velocities is not strictly correct. Since there is no experimental data on the temperature variation of the coefficient of expansion of beryllium, it is possible to obtain an extrapolated value from some of the other known properties of beryllium. The coefficient of volume expansion $\beta$ is related to the specific heat at constant pressure $C_p$, the specific heat at constant volume $C_v$, the isothermal compressibility $K_T$, the adiabatic compressibility $K_s$, the specific volume $v$ and the absolute temperature as follows.

\[ C_p - C_v = \frac{T \beta^2}{K_T} \]
\[ K_T - K_s = \frac{T \beta^2}{C_p} \]
\[ \frac{C_p}{C_v} = \frac{K_T}{K_s} \]

The values of $C_p$, $\beta$, and $v$ may be obtained for room temperature from the literature and handbooks and $K_s$ can be calculated from the room temperature velocity measurements. Substitution of these known values in the above equations allows one to determine $C_v$ and then $Y$ at room temperature. One could then extrapolate $C_v$ so as to ever approach the measured $C_p$ versus $T$ curve to where $T \approx C_v \approx C_p$ at about $15^o K$. It would then be possible to obtain $v \beta^2$ as a function of temperature. From this an approximate value of $\beta$ vs $T$ could be extrapolated. Such a process would give at best only a fair approximation to the volume expansion coefficient. It would probably be
Figure 13. Extrapolated round-trip travel distance, based on specific heat curve. Dotted line is based on the linear coefficient of expansion.
just as well to extrapolate the linear coefficient of expansion to the absolute zero by drawing a curve that behaves in the same manner as the specific heat vs T curve, and that approached zero asymptotically at near the absolute zero. On this basis the curve of twice the beryllium sample length versus temperature shown in Figure 13 has been obtained. Reference to Figure 13 shows that even if the linear relation held to the absolute zero the error between the extrapolated and linear curve would give an error in the velocity of only one part in a thousand which is inside the experimental error.

**TEMPERATURE VARIATION OF THE LONGITUDINAL AND TRANSVERSE VELOCITIES**

The length of the beryllium specimen was carefully measured to give a six significant figure value at 28° C. Assuming that the coefficient of expansion, as given in the Handbook of Chemistry and Physics, is correct, then the temperature variation of the length should be correct to four or five significant figures at least as low as 150° K. The uncertainty in the round-trip travel time, for a sound wave in the specimen, is in the fourth significant figure. The error in the velocities is therefore mainly due to the uncertainty in the timing measurements. This inaccuracy is, in itself, mainly due to the sound interference, as
previously discussed.

The temperature variations of the longitudinal and transverse velocities, as computed from the round-trip travel distance (Figure 13) and the round-trip travel times (Figures 10 and 11), are shown in Figure 14. On the basis of the estimated errors in the round-trip travel time the errors in the velocities are tabulated.

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°K to 40°K</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>40°K to 80°K</td>
<td>± 0.4%</td>
</tr>
<tr>
<td>80°K to 250°K</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>250°K to 300°K</td>
<td>± 0.3%</td>
</tr>
</tbody>
</table>

### Transverse Velocity

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3°K to 30°K</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>30°K to 80°K</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>80°K to 300°K</td>
<td>± 0.2%</td>
</tr>
</tbody>
</table>

**TEMPERATURE VARIATION OF THE ADIABATIC ELASTIC MODULI**

In computing the elastic moduli of beryllium from the measured values of the longitudinal and transverse velocities, the necessary relationships are taken from the
theory of elasticity as developed for homogeneous isotropic solids. Actually there exists no purely homogeneous and isotropic solid for which the theory really holds because most materials are composed of small crystallites or grains usually oriented at random throughout the body. For a solid to be homogeneous and isotropic it must have infinite symmetry; i.e., if a line is extended in any direction from a material point it must end on a material point. The separation distances between atoms in a grain or crystallite are finite and usually the atoms are arranged within the grain in an ordered fashion. Within each grain there is a certain amount of symmetry because of this ordering but of course the symmetry is not infinite. However, for randomly distributed grains the homogeneous isotropic theory is supposed to apply. Roth has found experimentally that there is only a negligible velocity dependence on grain structure. He did find, however, that the attenuation of the sound wave is a function of wavelength and grain size.

The beryllium specimen used in these experiments was supplied by the M. I. T. Metallurgy Department. They stated that the sample had a purity of 99.2 percent but gave no information as to its grain structure. On the basis of Roth's findings, however, one can be reasonably safe in calculating the elastic moduli from the homogeneous isotropic theory, even though the structure of the beryllium specimen is not known.
The wave equation for the propagation of a disturbance in a homogeneous isotropic media is derived in several texts on the theory of elasticity. This wave equation may be written in several forms depending on which two elastic moduli are taken as independent. If Young's modulus $E$ and Poisson's ratio $\sigma$ are taken as the independent moduli, then the wave equation is

$$\rho \frac{\partial^2 \vec{s}}{\partial t^2} = \frac{E}{2(1+\sigma)} \left[ \nabla^2 \vec{s} + \frac{1}{1-2\sigma} \text{grad} \text{div} \vec{s} \right]$$

where $\rho$ is the mass density of the material and $\vec{s}$ is the small vector displacement of material points due to the sound wave disturbance in the medium.

It is convenient to represent the wave equation in Cartesian coordinates since the end faces of the beryllium specimen are polished flat and the direction of propagation of the sound wave is caused to be perpendicular to the end faces by the way in which the quartz transducer is mounted. Choosing the $x$-coordinate axis for the direction of propagation and the $y-z$-plane for one end face and with the vector displacement given by

$$\vec{s} = \hat{i} u + \hat{j} v + \hat{k} w$$

the wave equation may be separated into three separate equations.

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{E(1-\sigma)}{(1+\sigma)(1-2\sigma)} \frac{\partial^2 u}{\partial x^2}$$
\[
\begin{align*}
(3) \quad \rho \frac{\partial^2 u}{\partial t^2} &= \frac{E (1 - \sigma)}{(1 + \sigma)(1 - 2\sigma)} \frac{\partial^2 u}{\partial x^2} \\
(4) \quad \rho \frac{\partial^2 v}{\partial t^2} &= \frac{E}{2(1 + \sigma)} \frac{\partial^2 v}{\partial x^2} \\
(5) \quad \rho \frac{\partial^2 w}{\partial t^2} &= \frac{E}{2(1 + \sigma)} \frac{\partial^2 w}{\partial x^2}
\end{align*}
\]

The equation (3) represents the propagation of a pure longitudinal wave in the \(x\)-direction while equations (4) and (5) represent the propagation of pure transverse waves in the \(x\)-direction. Because of this the remaining terms in \(\text{grad} \ (\text{div} \ \mathbf{F})\) vanish. The velocities of the longitudinal and transverse waves represented by equations (3), (4) and (5) are

\[
(6) \quad v_L = \left[ \frac{E (1 - \sigma)}{(1 + \sigma)(1 - 2\sigma) \rho} \right]^{\frac{1}{2}}
\]

\[
(7) \quad v_T = \left[ \frac{E}{2(1 + \sigma) \rho} \right]^{\frac{1}{2}}
\]

All of the other elastic moduli can be represented in terms of \(E\) and \(\sigma\). The adiabatic modulus of compression is

\[
(8) \quad k = \frac{E}{3(1 - 2\sigma)}
\]
and the shear or rigidity modulus is

\[ (9) \quad \mu = \frac{E}{2(1 + \nu)} \]

The adiabatic compressibility \( K_a \) is the reciprocal of equation (8).

If equations (7) and (8) are solved for Poisson's ratio, the result is

\[ (10) \quad \sigma = \frac{\frac{v^2}{v_t^2} - 2}{2 \cdot \frac{v^2}{v_t^2} - 2} \]

Because of the relations (8) and (9), equations (6) and (7) can be written in terms of \( k \) and \( \mu \) alone. This leads to

\[ (11) \quad v_l = \left[ \frac{k + \frac{4}{3} \mu}{\rho} \right]^{\frac{1}{2}} \]

\[ (12) \quad v_t = \left[ \frac{\mu}{\rho} \right]^{\frac{1}{3}} \]

The adiabatic elastic moduli \( E, \sigma, k, \mu \) as calculated from the smoothed velocity curves are given as a function of temperature in Figures 15 and 16. The adiabatic compressibility is given in Figure 16. Since the values of the elastic moduli involve the squares of the velocities, the uncertainty in their values are doubled.
Fig. 5.
Figure 16. Temperature variation of the adiabatic compressibility and Poisson's ratio of beryllium.
The following table gives the percent error over the various temperature ranges, based solely on the error in velocity measurement 5.

| Temperature Range     | % Error in k | % Error in  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20° K to 30° K</td>
<td>± 0.4 %</td>
<td>± 0.4 %</td>
</tr>
<tr>
<td>30° K to 80° K</td>
<td>± 1.0 %</td>
<td>± 0.8 %</td>
</tr>
<tr>
<td>80° K to 250° K</td>
<td>± 0.4 %</td>
<td>± 0.4 %</td>
</tr>
<tr>
<td>250° K to 300° K</td>
<td>± 0.6 %</td>
<td>± 0.4 %</td>
</tr>
</tbody>
</table>

Referring to Figure 16, it is seen that at 300° K the value of the adiabatic compressibility is 1.03 x 10^{-12} cm^2/dyne. Bridgman measured the isothermal compressibility of beryllium and obtained the value 8.85 x 10^{-15} cm^2/dyne at 30° C. Actually the adiabatic value should be smaller than the isothermal value and the 15 percent difference in these values warrants consideration. The velocity measurements are accurate over the whole length of the specimen to certainly 0.6% or better. If Bridgman's value is correct, then a plausible explanation of the failure to obtain about his value could be based on the possibility of a very large grain structure of the specimen used. Such a large grain structure could cause refraction and reflection at grain boundaries giving an incorrect velocity even though the measurements are very accurate. On the other hand, it is quite possible that Bridgman's value is incorrect since he reports that measurements were made on two different
specimens and about a five percent difference in the two values of the isothermal compressibility resulted. It is quite possible that beryllium specimens having different percentages of impurities and grain structures would have different compressibility values. Bridgman states that on one of his beryllium samples there were inclusions of the salt from which the beryllium was fused. For this specimen the compressibility was $9 \times 10^{-13}$ cm$^2$/dyne. His other specimen was a cast beryllium rod and on this sample the compressibility was $8.85 \times 10^{-13}$ cm$^2$/dyne. He makes no statement as to the purity of the beryllium. Recent techniques have made it possible to obtain beryllium specimens of very high purity so it is possible that the impurities in Bridgman's beryllium samples could have resulted in his low values of compressibility. The very high purity of the beryllium used in the present experiments gives a higher compressibility as has been stated. However, it is felt that this should be further checked and more accurate measurements should be made at perhaps a different frequency and on different pure samples in order to obtain a compressibility value that one could be reasonably sure of.

Herring and Hill have made a theoretical analysis of the constitution of metallic beryllium. Using Bridgman's value for the compressibility they obtained a value for the binding energy of beryllium of 53 kilogram
calories per gram atom. The value measured by Bickowsky and Rossini\(^{15}\) was 75 kilogram calories per gram atom. Herrings and Hill\(^{14}\) stated that this experimental value appeared to be nearer the true value than their theoretical result. The value of \(K_s\) obtained from the present experiment would perhaps bring their theory into better agreement with experiment.

**DISCUSSION OF THE OBSERVED INTERFERENCE EFFECTS**

As was stated previously, the second echo corresponding to the second round-trip through the beryllium specimen, was always of much smaller amplitude than the first and third echoes. In addition very weak signals occurred between echoes after the third, as shown in Figure 17a.

On the basis of experimental evidence and the following arguments, the cause of the interference effects is assumed to be due to inhomogeneities in the beryllium specimen. Such inhomogeneities may be in the form of very large crystallites or grains or in the form of cracks and air holes. It is possible that the interference with the second echo is due to sound energy that has been reflected or refracted back and forth between some grain boundary and the walls so as to arrive just in time to give interference with the second echo. It is immediately obvious that it is not due only to oblique reflections from the walls and
INTERFERENCE EFFECTS

Figure 17a. Oscilloscope picture at room temperature showing destructive interference with the second echo. The quartz transducer was mounted in the center of the face of the beryllium cylinder.

Figure 17b. Oscilloscope picture at room temperature showing less second-echo interference, although later echoes exhibited interference. The quartz transducer was mounted near the edge of the top face of the beryllium cylinder.
faces because the same second-echo-interference was observed for both the longitudinal and transverse cases. Furthermore in a very carefully smeltered sample of pure tin absolutely no interference was observed. In the transverse case the velocity is smaller and also the sound beam width is narrower than in the longitudinal case.

Additional experimental evidence was obtained when the quartz was mounted near the edge of the circular beryllium face instead of in the center. When this was done the amplitude of the second echo (Figure 18b) increased considerably although the amplitude of the third echo remained strong. Had the interference in this case been due to sound reflected from the walls and end faces, it should have been even more pronounced.

Just how the interference takes place is not known but the following analysis further shows that it is not due to portions of the sound beam that have reflected from the walls and end faces so as to give destructive interference with the second echo. The distribution of the intensity of the sound wave as a function of the angle $\theta$ (Figure 18a) is determined as follows. The analysis by Horse$^{16}$ of a vibrating flat faced piston, set in a plane wall, and radiating sound into the medium as in Figure 18a, appears to be applicable in this case. In Figure 18a, the circular quartz transducer is assumed to vibrate with a velocity $v_0 \exp(-2\pi i v t)$ and to radiate sound in front of the wall.
The pressure at a distant point \( P \) in the medium may be considered as the sum of all the pressure elements which are due to the sound from elements \( ds \) of the vibrating quartz surface. The pressure due to each element \( ds \) is given by

\[
dp = i \frac{(p_0 \gamma \psi_0) ds}{r_1} e^{2\pi i \nu (\frac{r_1}{v} - t)}
\]

where \( p_0 \) is the density, \( \nu \) the frequency, \( v \) the velocity and \( r_1 \) the distance from \( ds \) to \( P \). The factor \( r_1/v \) expresses the fact that the sound wave is retarded in phase by the time it reaches the point \( P \). The distance \( r_1 \) can be approximated in terms of the distance \( r \) from the center of the quartz transducer to \( P \). This center is also taken as the origin of coordinates. If the radius, \( a \), of the quartz is small compared to \( r \) then the approximation is from Figure 18a,

\[
r_1 = r - \rho \sin \theta \cos \phi
\]

Then with \( \frac{2\pi v}{\nu} = k \) the pressure element and \( ds = \rho \rho \phi \, d\phi \) the pressure is

\[
dp = \frac{iA}{r} e^{ik(r - \rho \sin \theta \cos \phi - vt)} \rho d\rho d\phi
\]

and the total pressure is

\[
P = \frac{iA}{r} e^{ik(r vt)} \int_0^a \int_0^{2\pi} e^{-ik \rho \sin \theta \cos \phi} \rho d\rho d\phi
\]
The last integral is the integral form of the Bessel function \( J_0(k \rho \sin \Theta) \) so that when integrated the pressure becomes

\[
P \approx \frac{i B}{r} e^{ik(r-\nu t)} \left[ \frac{2J_1(ka \sin \Theta)}{ka \sin \Theta} \right]
\]

The intensity \( I \) of the sound wave is proportional to the absolute value of the pressure and may be written

\[
I = \frac{C}{r^2} \left[ \frac{2J_1(ka \sin \Theta)}{ka \sin \Theta} \right]^2
\]

Since the velocity is \( 12.5 \times 10^5 \) cm/sec and the frequency used was \( 10^7 \) per sec, the value of the propagation constant becomes \( 47.5 \). Using this value for \( ka \), the argument of the first order Bessel's function \( J_1 \) is \( 47.5 \sin \Theta \). A plot of the above expression for \( I \), for distances \( r \) much greater than the radius of the quartz, is given in Figure 18b. The intensity \( I \) is the ordinate and the angle \( \Theta \) is the abcissa. The angular width of the half intensity points is called the beam width, which, in the case where \( ka = 47.5 \), turns out to be about 2 degrees on each side of the \( \Theta = 0 \) reference.

Reference to Figure 19a shows that the quartz crystal radius subtends about \( 3.6^\circ \) for the first echo; that is, for the sound pulse that has made just one round trip through the solid. This \( 3.6^\circ \) angle is, of course,

\[
\tan^{-1} \frac{a}{2d}
\]

where \( a = 0.95 \) cm is the radius of the quartz and \( 2d = 15.2 \) cm is the round trip travel distance. The
quartz radius subtends only about $1.8^\circ$ for the second echo in which case this angle is $\tan^{-1} \frac{a}{4d}$. It was determined experimentally that about 80 percent of the energy incident on the quartz was reflected, and about 20 percent was absorbed in producing the electrical signal. Figure 19a shows the beryllium specimen extended on itself to illustrate two round trips through the specimen. The dotted part of Figure 19b represents the intensity distribution just before the second echo is produced. The solid curve in Figure 19b shows that 80 percent of the energy subtending an angle of $3.6^\circ$ about the center of the beam is absorbed in producing the electrical signal. Only the very small intensity annular ring portion of the signal from $3.6$ degrees to $3.8$ degrees reflects from the top face without undergoing 20 percent absorption. Even for the second echo this small intensity ring has not reflected from the walls so that it could not produce interference. The dotted part of the curve Figure 19c is the intensity before the second echo is produced, and the solid part represents the intensity after the quartz has absorbed 20% of the energy incident upon it. Since the quartz radius now subtends only $1.8$ degrees, as shown in Figure 19c, only the portion illustrated is absorbed. Only for echoes after the second, has the sound beam reflected from the walls sufficiently to give constructive
Figure 19. Illustrating that no interference with second echo arises from reflection of sound from walls of specimen.
or destructive interference. It is therefore concluded that second-echo interference cannot be due to geometrical reflection from the walls.

It was also thought that the interference might be due to early parts of the signals traveling through the thin quartz plate, reflecting, and arriving back at the boundary between the quartz and solid so as to cause interference. It was shown experimentally that this also does not explain the interference. To show this a thicker 3.3 Mc/sec quartz transducer crystal was operated on its third harmonic instead of the usual thin 10 Mc/second quartz. No change was noted in the interference pattern when this was done.

On the basis of the experiments and the above analysis it is concluded that this interesting interference phenomena must be due to inhomogeneities in the metallic beryllium. Just how it takes place is not known.

CONCLUSIONS

An interesting result of these present experiments is the high observed value of the longitudinal velocity. It is also interesting that the Poisson's ratio has such a low value of about 0.01, while most other metals have a value of 0.2 to 0.3. The most malleable metals have the highest value Poisson's ratio while the brittle metals have, in general, a low value. The extremely low value
of 0.01 for beryllium appears to confirm the fact that it is one of the hardest metals, although the Poisson's ratio must change from this value to \( \frac{1}{3} \) at the melting point because the value for all liquids is \( \frac{1}{3} \). Whether beryllium undergoes this change suddenly, or gradually over a large temperature range, is not known.

The hump in the velocities and moduli in the range from 200° K to 300° K warrants some investigation. One would expect that such a change in the elastic properties would also manifest itself in a similar change in the coefficient of expansion although there is no experimental evidence to verify such a statement.

In view of some of the uncertainties in the experiments, it is felt that measurements should be made on a different frequency, say 30 Mc/sec. in order to further confirm the observed interference phenomena and to obtain more accurate velocity measurements. In the region of the anomalous specific heat hump of beryllium near 12° K, the accuracy of velocity measurements was not good enough to allow a decision as to whether a change in elastic properties or electronic specific heat is the cause of the hump. A more precise measure of the velocities, on a frequency which lends itself to higher accuracy, appears to be a logical step.
ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to Dr. C. F. Squire for suggestion of the problem, for taking part in many long and helpful discussions concerning the progress of the work and the concepts involved in the interpretation of the observed phenomena and as well as for supervising overall operations of the Rice Institute Helium Cryostat during the process of the experiments.

He also wishes to thank Mr. R. F. Blunt, Mr. R. Schmidt, Mr. N. Skomal and Mr. W. Love for assisting during the experiments and Mr. R. H. Pry for helpful discussions concerning ultrasonic interference phenomena.
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