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SOME THERMAL AND ELECTRICAL PROPERTIES OF BERYLLIUM

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ABSTRACT

Specific heat.—The specific heat of beryllium was obtained from cooling data by equating the heat loss per cm length per unit time from beryllium to that from zinc. The values obtained increase rapidly with a rise in temperature from 0.0389 at −175.6°C to 0.593 at 190°C.

Thermal conductivity.—The modified Forbes method of Bidwell was used to determine the thermal conductivity of this metal. Values of k were calculated with three different sets of distances from the first junction as origin for each run at a given surrounding temperature. k was found to increase with a rise in temperature from 0.232 at −176.2°C to 0.508 at 190.4°C.

Specific resistance.—The specific resistance varies according to the heat treatment given the sample. Values recorded in this article are those obtained after a steady condition had been established after repeated treatments from liquid air temperature to 700°C. Measurements made on two samples check each other closely. They are: 1.56 microhms at −191°C; 6.76 microhms at 22°C; 19.05 microhms at 305°C; and 40.00 microhms at 690°C.

Temperature coefficient of resistance.—The temperature coefficient of resistance, α, is not a constant over the above range. It increases with a rise of temperature but not linearly. The graph of this quantity plotted against temperature shows three distinct sections, α has the following values: 0.000371 at −190°C; 0.00667 at 20°C; 0.00800 at 310°C; 0.00858 at 500°C; and 0.01196 at 685°C.

Thermoelectric power.—The thermoelectric power of beryllium against lead seems to vary linearly with temperature. However, at −50°C the graph of the thermoelectric power plotted against temperature shows a break. This, considered in connection with the results obtained for the temperature coefficient of resistance, suggests the probability of a change in allotropic form.

Wiedemann-Frantz-Lorentz law.—The Wiedemann-Frantz-Lorentz law, that $k/\sigma T$ is a constant, is not obeyed by this metal.

THREE years ago, soon after beryllium could be obtained in a highly pure state, it was thought desirable to determine certain of the physical properties of the metal.[1] The specific heat was determined in conjunction with the thermal conductivity over the range from liquid air temperature to 200°C, the thermal conductivity being determined by the modified Forbes method of Bidwell.[2] However, the writer introduced one change by bringing the junction

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[1] A rod of beryllium, commercially pure, was obtained from the Beryllium Company of America. This showed, when analyzed spectroscopically, traces of aluminum, manganese and chromium, and smaller traces of iron, silicon and magnesium, a total of about 0.5 percent. In addition, x-ray shadow pictures of the sample showed physical imperfections to be so small that they could be neglected without introducing any appreciable error in the calculations.

[2] Bidwell, Phys. Rev. **28**, 584 (1926).

leads out to the edge of the fiber disks and then parallel to the axis of the sample to the top of the containing tube, thus allowing better radiation from the sample to the surrounding constant temperature baths. Investigations of specific resistance and temperature coefficient of resistance were carried out over a much greater range of temperatures, liquid air to 700°C. The thermo-electric power against lead was determined only over the range from liquid air temperature to 200°C. Using the results obtained for the thermal conductivity and the specific resistance the Wiedemann-Frantz-Lorentz relation was calculated.

SPECIFIC HEAT

Procedure. The determination of the specific heat of beryllium was made from cooling data. A piece of the original beryllium sample 6 cm long and a zinc rod of about the same length but of exactly the same diameter were each mounted with a single junction and three disks in the Pyrex tube used later for gradient data. Cotton plugs were inserted above and below these small rods to prevent heat losses through the ends. Readings of the junction were taken every half minute as each rod cooled through the range of temperatures possessed by various parts of the rod in the thermal conductivity experiment. Several runs were taken on each metal. In order to obtain an average of the runs the readings were plotted against time. One run was plotted and a smooth curve drawn; then the other runs were plotted so as to coincide with the first at the middle of the temperature range needed for determining the thermal conductivity. Then an average curve was drawn through all points plotted. The micro-volt readings used in calculating the specific heat were taken from this average curve.

According to Newton's Law of Cooling, heat loss per cm length is the same for all metals provided the surface is the same and the dimensions of the apparatus are the same. These conditions were met as the cooling data were taken in the tube used for the gradient data and the samples had the same diameter. To make sure that slight variations in the character of the surfaces of the two samples had no effect, runs were made having a coating of soot on each specimen. Within the experimental error this yielded no change in the specific heat. The heat loss curve plotted against temperature is a nearly straight line over a range of 20°C and in the results here reported the range was never more than 6°C. Thus the following equation may be written

$$(1/L\cdot M\cdot S\cdot dT/dt)_{Be}=(1/L\cdot M\cdot S\cdot dT/dt)_{Zn}$$

for any one temperature, where L is the length, M the mass, S the specific heat, and dT/dt the rate of cooling. The specific heat of beryllium was determined from the above equation using the specific heat of zinc determined by drawing a mean graph through all the values given by Landolt and Börnstein.

Results. The results of the specific heat measurements are found in Table I and Fig. 1. Over the range from liquid air temperature to 200°C the specific heat, S, increases with increase in temperature. At −175.6°C the value of

S is 0.0389. Dewar[3] gave 0.0137 as the average specific heat over the range -253°C to -196°C. Humpidge[4] gave a value of S equal to 0.445 from 45°C to 50°C, while the value found in this experiment taken from Fig. 1 is $S=$ 0.457 at 50°C. The work of Nilson and Pettersson[5] in 1881 gives the average specific heat from 0°C to 300°C as 0.5060 which is lower than found in this experiment, 0.565 at 150°C. Thus the values obtained in the present investigation agree quite well with those reported by early observers.

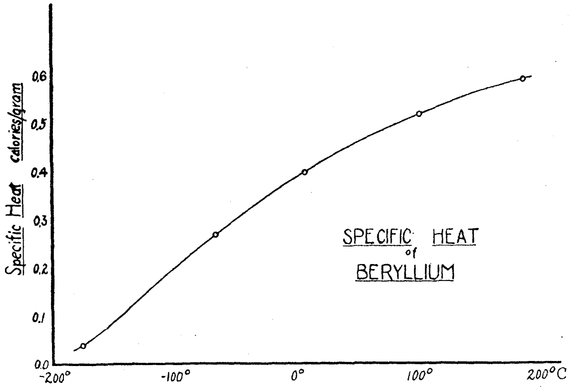

Fig. 1. Specific heat of beryllium.

TABLE I. *Specific heat of beryllium.*

Various Points	Temp.°C	Specific Heat.
Liquid Air	-175.6	0.0389
CO_2 Snow	-65.0	0.270
Ice-Water	9.5	0.399
Hot Water	104.0	0.519
Hot Air	190.0	0.593

THERMAL CONDUCTIVITY

Apparatus and procedure. The specimen of beryllium in the form of a rod 21 cm long and 1 cm in diameter was heated at one end by a coil of about 20 turns of asbestos covered nichrome wire. This was insulated from the rod by two layers of mica. Starting 1 cm from the heater coil copper-advance junctions (#29 wire) were placed spirally along the rod at intervals of 2.5 cm and 60°. The junctions were silver soldered and mounted in small holes (No. 60 drill) by wedging in small pieces of copper wire to make a good contact. Great care was taken to have the junctions as near the surface as possible. The specimen was slipped into a Pyrex glass tube 2.5 cm in diamter, 40 cm long, and closed at the lower end. All junction leads and heater coil leads

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[3] Dewar, Proc. Roy. Soc. **A89**, 158 (1913).

[4] Humpidge, Proc. Roy. Soc. **35**, 137 and 358 (1883).

[5] L. F. Nilson and O. Pettersson, Berichte **13**, 1451 (1881).

were brought out the top of the tube and cotton was stuffed in the top of the tube to cut down convection currents. The tube containing the specimen was placed in a Dewar cylinder 40 cm long and 6.6 cm in diameter. Constant temperature baths were obtained by filling the Dewar in turn with liquid air, CO_2 snow and ether, and water. A higher temperature was obtained by a hot air jacket. As soon as the readings of the junctions reached the temperature of the bath, indicating that a steady state had been reached, the top of the rod was heated by means of the heater coil until the top junction read about 10° higher than that of the surrounding bath. After about an hour readings of each junction were taken and repeated until a steady state had established itself. Usually the rod was later allowed to cool down to the temperature of the surroundings and another set of "zero" readings taken. This permitted discrepancies in junction readings to be taken into account. Cooling data taken as previously described were used again in the calculation of the heat loss per cm length per unit of time.

The CO_2 snow and ether were placed in the Dewar cylinder and stirred from time to time, as was the liquid air, to keep the temperature as uniform as possible. For the point near 0°C icewater was pumped out of the bottom of a pail of cracked ice into the bottom of the Dewar and allowed to run out at the top and trickle down through the ice again. In this way a very uniform temperature of about 0.5°C above zero was maintained. A higher temperature of about 98°C was obtained by pumping boiling water through the Dewar. The highest surrounding temperature was obtained by use of a double-walled brass cylinder heavily lagged to prevent radiation, through which heated air was flowing at a constant rate.

The relative temperatures along the rod were obtained by dividing the difference in micro-volts between two junctions by the micro-volts per degree for the particular temperature obtained from the calibration equation of the junction.[6] Relative temperatures along the rod were known to within 0.05°C at the lower temperatures and much better than that for the higher temperatures as the micro-volts per degree increase with a rise in temperature. Actual temperatures may have been uncertain as much as one degree at the most.

The theory of the method has been very clearly given in detail by Bidwell in the article previously mentioned. After obtaining the temperatures at fixed points along the rod, measured from the first junction at the hot end as origin, the method is essentially a graphical one. It depends on the slopes and intercepts of graphs, one of which is dT/dx against T and another the heat loss per unit time plotted against temperature. From these graphs together with three others also mentioned by Bidwell the constants are obtained which, when substituted directly in a relatively simple formula, give the value of k at once.

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[6] The junctions used were calibrated against junctions which had previously been calibrated by the United States Bureau of Standards as follows: one pair of copper-advance junctions for the range 0°C to liquid air temperature, accurate to ±0.2°C, and another pair of the same materials for the range from 0°C to 350°C, reliable to ±0.5°C. For the higher temperatures used in the specific resistance experiment chromel-alumel junctions were used which were good to ±3.0°C.

Discussion of results. The values of the thermal conductivity of beryllium are given in Table II. It will be seen that *k* has been calculated for three different sets of distances from the origin and that the value of *k* decreases as the origin is approached in all cases. The general trend of an increase in the value of the thermal conductivity with increase in temperature is clearly shown in Fig. 2 where the grand average values are plotted.

TABLE II. *Thermal conductivity.*

Temp.	*k* 5–10	*k* 4–9	*k* 3–8	Av. *k* 3–10	Av. Temp.	Grand Av. *k*	Grand Av. Temp.
Liquid Air							
−176.04			0.202				
−176.37		0.220					
−176.64	0.242			0.221	−176.37		
−175.30			0.204				
−175.61		0.235					
−175.91	0.270			0.236	−175.61		
−176.10			0.201				
−176.55		0.238					
−176.81	0.277			0.239	−176.49	0.232	−176.2
CO_2 Snow							
−65.91			0.308				
−66.18		0.342					
−66.43	0.381			0.344	−66.17		
−63.53			0.277				
−63.85		0.299					
−64.08	0.338			0.305	−63.82	0.325	−65.0
Ice-Water							
9.53			0.358				
9.31		0.379					
9.05	0.409			0.382	9.30		
9.71			0.372				
9.42		0.393					
9.18	0.423			0.396	9.44		
9.63			0.361				
9.36		0.399					
9.10	0.441			0.400	9.36	0.393	9.4
Hot Water							
105.57			0.454				
105.21		0.468					
104.88	0.492			0.471	105.22		
105.63			0.426				
105.18		0.440					
104.87	0.462			0.442	105.23	0.457	105.2
Hot Air							
190.67			0.470				
190.40		0.501					
190.17	0.552			0.508	190.40	0.508	190.4

The lowest surrounding temperature was obtained through the use of liquid air, as liquid oxygen or hydrogen was not available. This becomes warmer the longer it stands and also during use, as the nitrogen evaporates first.

On this account it is very difficult to have the gradient data taken with the same surrounding temperature as the cooling data. Since this method depends on constants obtained from graphs this introduces an error. The exact temperature may be in error as much as 1°C due to the uncertainty of the junction itself for all temperatures below 0°C. Mounting the junctions also introduces an error as it is impossible to be sure that all the junctions are exactly at the surface of the sample. Thus it can be easily seen how, between extremes, a maximum experimental error of 4.7 percent based on the mean may have crept into the work.

CO_2 snow also presented all of the above sources of error, even that due to non-uniform temperature down the cylinder, as there was no free circulation in the ether slush so that some portions of the tube might have been warmer than others thus giving poor gradient data. The average of k for one run at this temperature is probably low. The value of $k = 0.344$ for the other run appears, by comparison with values of k at other temperatures, to be the more nearly correct value. In fact this point would fall almost exactly on the smooth curve, Fig. 2. In all this work the data from which the calculations were made are the averages of twelve different sets of observations. The maximum error here is probably not greater than 5.9 percent.

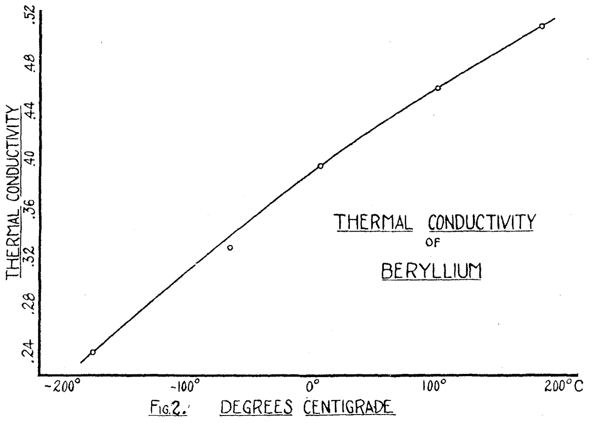

Fig. 2. Thermal conductivity of beryllium.

When ice-water was used as a means of obtaining a surrounding temperature near 0°C, very much better control resulted so that here the maximum error was 2.8 percent. This was obtained because of the good circulation maintained by the pump as previously mentioned. Boiling water was used in a similar manner and the deviation from the mean was 3.1 percent.

A temperature near 200°C was obtained by the use of circulating hot air and did not prove to be as satisfactory as water in maintaining a constant temperature, due to its low specific heat and density. The radiated heat was not carried away fast enough so the surroundings became warmer during the run, thus affecting both the gradient data and the cooling data. The value of the thermal conductivity at this temperature may be in error as much as 5 percent.

The equation of the graph, Fig. 2, is given by

$$k=0.3847+0.000751t-0.000000468t^2-0.00000000027t^3$$

where k is the thermal conductivity and t the temperature in Centigrade degrees.

In this work it has been assumed that the temperature has been uniform over the cross section of the rod. This is an assumption which is not true because moving any one junction toward or away from the axis of the sample changed the relative temperature between it and the two adjacent junctions which remained fixed, thus showing the cross section was not an equal temperature surface. At the top close to the heater coil the heat flow lines are toward the center so that the equal temperature surface is convex upward, while at the lower end just the reverse is true. For this reason the temperatures recorded are not the exact ones for equal temperature surfaces through the given distances from the origin. This source of error would be very much less if a rod three or four times as long were used. The writer feels that the specimen he used was entirely too short because in working up the graphs more reliance had to be placed on the central junctions than on those at the ends. It would seem that these two sources of error are responsible for the large experimental errors obtained using the various sets of distances in calculating k.

Specific Resistance and Temperature Coefficient of Resistance

Apparatus and procedure. The specific resistance of beryllium was found by passing a small current of less than an ampere through a rod of beryllium, 0.792 cm^2 in area, and a recently calibrated resistance in series. A Wolf potentiometer was used to measure the potential drop across the standard resistance and between two leads inserted 22.5 cm apart in the beryllium rod. Another determination was made with a rod of 0.803 cm^2 in area and 18 cm between potential leads. In these experiments the distance between the potential leads is known to within 0.05 cm as the holes used were small (No. 60 drill) and No. 22 copper wire was wedged into them with small pieces of the same wire. Slotted copper connectors were slipped over the ends of the sample and fastened by means of steel rings and set screws and the current leads were fasted to these connectors by screws. The contacts thus made were sufficiently good to eliminate local heating. Two pairs of thermo-junctions were placed in the sample, one to read the temperature near one end and the other in the middle. The two pairs of junctions used at any given temperature did not always read alike so that the rod was not at a uniform temperature. Therefore to obtain the correct potential difference over the rod both direct and reverse readings were taken to eliminate any e.m.f. set up by the Be-Cu junction formed by the rod and leads.

For the lower temperatures the rod was immersed in liquid air and CO_2 snow and ether. These were stirred constantly during the time the readings were taken. For the higher temperatures the sample was supported on mica inside of a brass cylinder which was surrounded by a well insulated electric furnace.

Each of the two samples was heated to about 700°C and cooled down to nearly room temperature and readings taken every few degrees. This was repeated until the results were reproduced within the accuracy of the thermojunctions.

The coefficient of specific resistance was determined by finding for different temperature ranges the third degree equations of the graph obtained by plotting the specific resistance against temperature. These were differentiated with respect to temperature giving equations of the form

$$d\rho/dT = a + bT + cT^2.$$

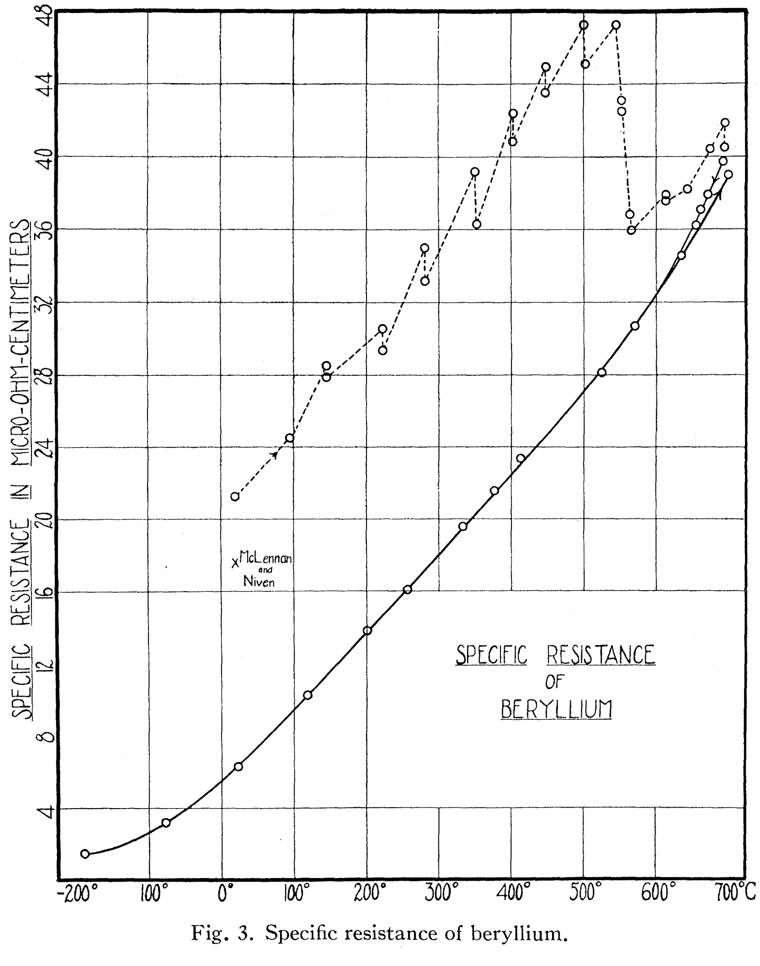

Fig. 3. Specific resistance of beryllium.

The temperature coefficient of resistance, α, was found by dividing the computed values of $d\rho/dT$ by ρ_0, the resistance at 273°K.

Results. The results of the specific resistance measurements on sample 1 are shown graphically in Fig. 3 and are tabulated in Table III. It will be seen that the sample yielded considerably to heat treatment. From this curve it can be easily seen how a great many values of the specific resistance can be obtained for any given temperature, depending upon at what stage of its heat treatment the observation is made. The rather high value of 17.6 microhms at 20°C reported by McLennan and Niven[7] may have been due to not carrying the heat treatment over so wide a range of temperature. Fig. 3 shows that the first measurements taken at room temperature (22.5°C) gave a value of 23.0 microhms. The measurements for the specific resistance on this sample were first continued only to 455°C when the junction oxidized and broke. When the run was continued and another measurement made at room temperature (22.5°C) ρ was found to have a value of 21.5 microhms indicating that some change had taken place. As the temperature was increased in steps of about fifty degrees and held constant for some time, a decrease in the value of ρ resulted. However, between 545°C and 562°C ρ decreased from 47.3 microhms to 36.0 microhms indicating a decided change had taken place at about this temperature. The specific resistance continued to increase with a rise in temperature at about the same rate as it did before the sudden decrease in ρ. Another decrease was observed at about 670°C. Most of the change had taken place by this time as measurements made later when the temperature was both increasing and decreasing from room temperature to 700°C checked each other within the limits of accuracy of the junctions used to read the temperature.

TABLE III. *Specific resistance of beryllium.*

Sample 1*		Sample 2	
Temp.	$\rho \times 10^6$	Temp.	$\rho \times 10^6$
−189°C	1.50	−191°C	1.56
−77	3.22	−77	3.33
+21	6.45	+22	6.76
108.5	9.75	97	9.83
223	14.64	212	14.85
315	18.60	305	19.05
401	22.45	403	23.90
512	27.55	504	29.00
607	32.45	604	34.55
700	39.00	690	40.00

* This was the sample analyzed.

A second sample was then measured after it had first been given a heat treatment. The temperature was slowly increased over a period of 24 hours to about 700°C and held there for 12 hours and then cooled slowly to room temperature. This process was repeated to insure a steady condition of the sample as only the specific resistance in such a state was desired. The results for this sample are shown in Table III from which it can be seen that the specific resistance of sample 2 checked well with that of sample 1. The final

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[7] McLennan and Niven, Phil. Mag **4** (1927).

value of ρ at 25°C for sample 1 was 6.5 microhms and for sample 2 was 6.7 microhms.

Since the specific resistance of the two samples checked so well, the temperature coefficient of resistance was determined only for sample 2 and the values obtained are shown in Table IV and Fig. 4. The graph of the temperature coefficient appears to have three distinct parts, one from −190°C to about −50°C where the temperature coefficient rises rapidly from 4×10^{-4} to 56×10^{-4}, the second from about 50°C to about 400°C where the increase is nearly linear and with a smaller slope rising from about 72×10^{-4} to 82×10^{-4}, and the third in the range of about 500°C to 700°C where the coefficient rises

TABLE IV. *Temperature coefficient of resistance.*
$\rho_0=5.88\times10^{-6}\Omega$

Temp.	α*	Temp.	α	Temp.	α
−190°C	0.000371	+100°C	0.00722	+450°C	0.00844
−160	0.00169	140	0.00737	480	0.00864
−130	0.00287	180	0.00752	520	0.00899
−100	0.00391	220	0.00769	550	0.00938
−70	0.00481	250	0.00781	580	0.00983
−40	0.00556	280	0.00791	610	0.01035
−10	0.00619	310	0.00800	640	0.01094
+20	0.00667	360	0.00808	670	0.01160
50	0.00701	380	0.00817	685	0.01196
75	0.00712	410	0.00825		

* These values of α were obtained from six different equations, successive ones of which overlapped each other in temperature range.

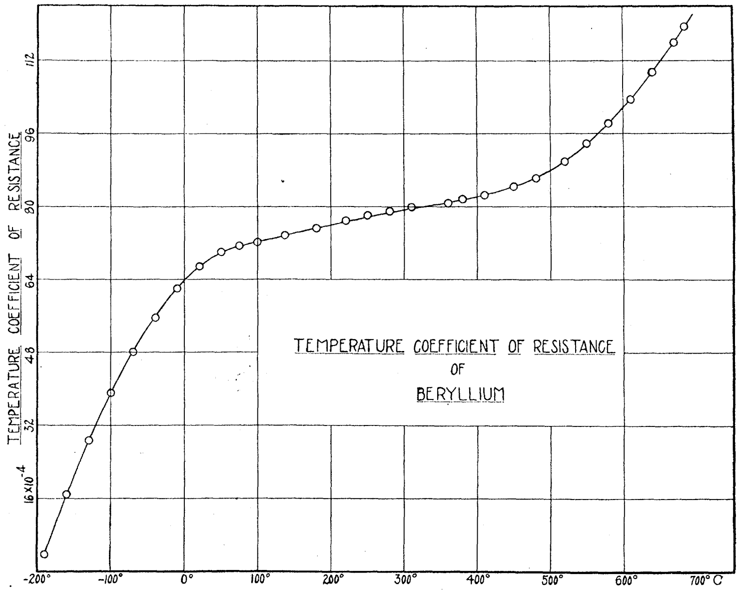

Fig. 4. Temperature coefficient of resistance of beryllium.

more rapidly again from 88×10^{-4} to 120×10^{-4}. These results quite strongly indicate that within the temperature range $-190°C$ to $700°C$ the sample passes through two allotropic transformations. Additional evidence of such a transformation at the lower temperature is seen in the thermoelectric power graph, Fig. 5, which has a break between $-50°C$ and $20°C$. The thermoelectric power was not measured at a sufficiently high temperature to determine whether another break occurs at about 450°C.

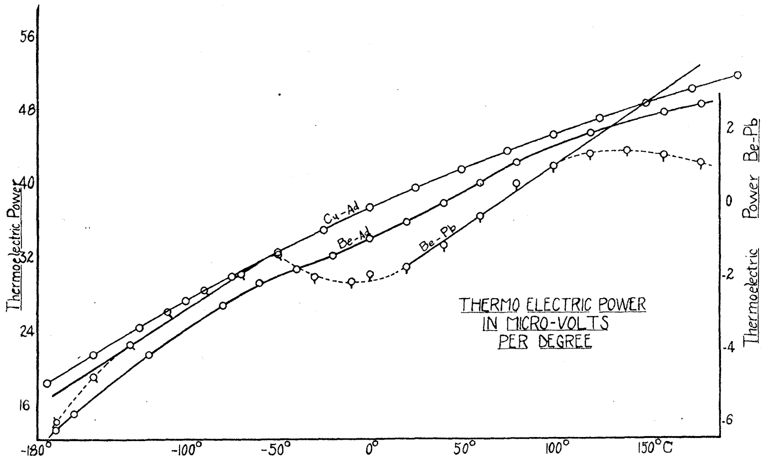

Fig. 5. Thermo-electric power (microvolts per degree) of beryllium.

THERMOELECTRIC POWER

Apparatus and procedure. The thermoelectric power of beryllium was obtained by first determining the electromotive force given by a beryllium-advance thermo-junction. The equation of the graph obtained by plotting the electromotive force against the temperature was differentiated giving an equation of the form

$$dE/dt = a + bt + ct^2$$

which is by definition the thermoelectric power. Experimentally this was difficult, as the rod of beryllium previously mentioned had to be substituted for a wire. In order to accomplish this two small holes (No. 60 drill) were made in the same transverse plane and close together near each end. A Pyrex cup 4 cm in diameter and 10 cm long, drawn down at one end to fit the rod, was slipped over it a distance of one third its length and a tight joint made with rubber tubing. A copper-advance junction was fastened into one of the holes at either end for reading the temperature, while in the other two were fastened advance wires by wedging in pieces of the same wire. The lower end with its wires was immersed in cracked ice while in the cup were placed, in turn, liquid air, CO_2 snow and ether, boiling water, and boiling nitro-benzol. The latter two liquids were heated by an electric heating coil. Also a small heating coil was wound around the sample itself while using the cold liquids, to prevent the lower end from becoming colder than 0°C. The liquids in the cup and the ice were stirred constantly during the time the readings were taken.

The thermoelectric power of beryllium against advance wire was then plotted. Beryllium is positive to advance. On the same graph the thermoelectric power of copper against advance was plotted. This was taken from the Bureau of Standards' calibration of a Cu-Ad junction. Copper is positive to advance and higher than beryllium. The differences in the thermoelectric power were read from this graph, Fig. 5. Thus the thermoelectric power of Be with respect to Cu was obtained.

From the Smithsonian tables the thermoelectric power of copper with respect to lead is given by

$$dE/dt = 1.34 + 0.094t \ .$$

However, here lead was wanted against copper, so all the signs were reversed. Since the thermoelectric power of lead and beryllium are both against copper, the thermoelectric power of beryllium against lead is obtained by subtraction.

Results. The final result of the thermoelectric power of beryllium referred to lead appears to be represented by two straight lines not quite parallel to each other and broken by an offset between -50°C and 20°C, Fig. 5, which indicates a change has taken place in the beryllium in this range, an indication that is in agreement with the results shown in Fig. 4. At the higher temperatures 100°C to 200°C the values do not follow the straight line. Also from -100°C down the experimental values do not follow the straight line. This may possibly be explained if the fact that a rod of beryllium was used instead of a wire is taken into account. It is a very hard matter experimentally to maintain a temperature gradient of nearly 200°C down a rod 0.792 cm^2 in area in a length of 17 cm. It may however be definitely stated that Be and Cu have values of thermoelectric power very close to each other.

WIEDEMANN-FRANTZ-LORENTZ-LAW

Since the specific resistance and thermal conductivity of beryllium have been determined, it seemed advisable to calculate the Wiedemann-Frantz-Lorentz relation which when put in a simplified form is

$$k/\sigma T = K = 24.7 \times 10^7 \ .$$

when k is expressed in ergs and σ in e.m.u. This does not hold for beryllium as is seen in Table V. In order for the law to hold for this metal the values of k would have to decrease instead of increase with a rise in temperature. Assuming σ to be correct the value of k should be 0.22 at 0°C and at 180°C k should equal 0.20.

Aluminum also shows a rise in thermal conductivity with a rise in temperature. The Wiedemann-Frantz-Lorentz Constant for aluminum is 13.2×10^7 at -189°C and 19.3×10^7 at 0°C and only 22.2×10^7 at 200°C. The value at 200°C is 1.68 times the value at -189°C whereas for beryllium the value at 180°C is 3.6 times the value at −170°C. Thus according to the data taken on these samples this law does not hold for beryllium.

TABLE V. *Values of thermal and electrical conductivities of beryllium.*

Temperature	k	σ	$k/\sigma T$
−170°C	0.251	5.88×10^{-4}	17.4×10^{7}
−150	0.268	5.23	17.4
−130	0.284	4.52	18.4
−110	0.300	3.84	20.0
−90	0.316	3.29	22.0
−70	0.332	2.82	24.2
−50	0.348	2.42	27.0−
−30	0.363	2.08	30.1−
−10	0.378	1.82	33.2
0	0.386	1.70	35.0
20	0.400	1.51−	38.1
40	0.414	1.34−	41.4
60	0.428	1.21−	44.7
80	0.441	1.10−	47.7
100	0.454	1.00	51.2
120	0.468	0.925	54.2
140	0.479	0.855	56.8
160	0.492	0.796	59.8
180	0.503	0.745	62.5

The writer wishes to express his thanks to Professor Bidwell for suggesting this problem, to Professors Collins and Gibbs for their helpful suggestions in carrying through the investigation, and to Professor Papish who made a spectrum analysis of the beryllium rod.