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THE IONIZATION OF GASES AT HIGH PRESSURES

A Thesis

Submitted to the Faculty of The Graduate School of The
University of Minnesota for the Degree of Doctor of Philosophy

by

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Minneapolis, Minnesota
1908

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-THE IONIZATION OF GASES-
AT HIGH PRESSURES

The ionization produced in gases by the different ionizing rays has not heretofore been studied for pressures much greater than one atmosphere*. It is of considerable interest, however, to know how the ionization and the rate of recombination change as the density of the gas becomes considerable and approaches that of the liquid state.

In the experiments to be described the ionization produced by the gamma (γ) rays of radium was studied for pressures up to 400 atmospheres in the case of air, and up to the liquefying point in the case of carbon-dioxid.

The results obtained will be presented, after a description of the apparatus, under the following subdivisions:

Results for air;

- 1- Ionization current at different pressures and potentials,
- 2- The time required for the rays to produce the steady state,
- 3- The lingering of the ions,
- 4- The time required to collect the ions,
- 5- The ionization current at different

*Phil. Mag. p.283, Vol. 3 (1902).

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temperatures.

Results for carbon-dioxid;

- 1- The lingering of the ions,
- 2- Ionization current at different pressures and potentials,
- 3- The natural conductivity of CO_2 at different pressures and temperatures,
- 4- The ionization current at different temperatures.

Summary and Conclusions.

-APPARATUS-

A diagram of the apparatus used in the experiments is given in Fig.1.

A is an iron cylinder 84 centimeters in length and 20.3 centimeters in diameter. Along the axis of the cylinder is a hole (S) 5.1 centimeters in diameter, closed at each end by means of the two steel plugs (M and N) which have two threads to the centimeter and are made tight by means of lead packing.

The upper end of the hole (S) is lined with brass and serves as the ionization chamber, the inside dimensions of which are 16.7 centimeters in length and 4.9 centimeters in diameter. The electrodes are made of brass gauze 0.04 centimeter in thickness and are concentric cylinders separated on the average

Fig.1.

by 0.8 centimeter. The inner cylinder and the lining of the chamber form one electrode and are connected to the iron cylinder (A), while the other cylinder and the central wire form the other electrode T, and are insulated from A. The insulated electrode (T) is supported by a brass rod passing through a hard-rubber plug provided with a guard ring (D). This brass rod has a shoulder near the inner end and is threaded at the outer end, the nut on which serves to tighten the entire plug, the gas pressure alone on the inside not being sufficient to prevent leakage.

A brass thimble 0.22 centimeter in thickness projects into the ionization chamber at B. This thimble is set in lead packing and is held in place by the hollow, threaded, steel plug (R) to which is attached axially a slotted metal tube one meter in length.

A metal tube containing the radium salt can be placed inside the thimble and the penetrating gamma rays allowed to ionize the gas in the ionization chamber. The tube of radium may be quickly withdrawn by releasing a stretched spiral spring attached to it.

The insulated electrode (T) is connected to two

Mc Lennan keys (E) and (F) and then to the leaf of a Wilson form of gold-leaf electroscope (G). C is a condenser of 0.001 microfarad capacity and is used to increase the capacity of the electrode system, the purpose being to decrease the rate of motion of the leaf of the electroscope.

When the iron cylinder is given a potential different from that of the earth, a current begins to flow between the electrodes because of the ions produced in the gas by the gamma rays. If now the electrode (T) is insulated from the earth by opening the key F, the leaf of the electroscope begins to move and the time (t) required for its image to pass a given number of divisions on the scale in the eyepiece of the microscope can be determined. Knowing the capacity C' of the electrodes and the potential (V) necessary to deflect the leaf the given number of divisions, the absolute value of the current may be determined from the relation

$$I = \frac{C'V}{t} .$$

In order to determine the number of ions present in the gas at any instant it is necessary to make a number of consecutive connections. This is accom-

plished by means of the pendulum P. The arrangement is such that as the pendulum reaches H it shuts off the rays by releasing the spring which withdraws the radium from the cylinder, at I it opens the key E, at J it connects the cylinder to the battery Q, at K it disconnects the battery and connects the cylinder to earth, at L it insulates the leaf of the electro-scope, at M it connects the electrode to the electro-scope and at N it *opens* again the key E.

The electroscope was found much more convenient than the quadrant electrometer in this investigation, as the inappreciable inertia of the leaf permits an observation to be repeated very quickly and easily.

Fig.2.

Fig.2 gives the calibration curve for the electro-scope and shows the range used in the current readings. The same sensibility was used throughout the entire investigation, the sensibility selected being determined by the size of the available capacity (C), the strength of the currents involved and the magnitude of the charge present in the gas at any instant.

The potential on the plate of the electroscope was obtained from a battery of fifty large lead chloride cells. The potentials of the cylinder up to one thousand volts were obtained from a high potential storage battery and potentials higher than one thousand volts were obtained by means of a small static machine in conjunction with a large battery of Leyden jars.

The radioactive substance used was about 0.6 grain of a salt containing 1% of radium bromide.

-RESULTS FOR AIR-

In the case of air, pressures up to two hundred atmospheres were obtained by means of a Whitehead compressor belonging to a liquid air plant and pressures higher than two hundred atmospheres were obtained

by means of a Cailletet hand compressor, the liquid used in it being paraffin-oil. The air used was purified by passing through lime before entering the compressor and then after being compressed it was passed through a cylinder containing caustic potash. In part of the work the air was also passed through a quantity of cotton just before entering the ionization chamber in order to remove any dust that might be present.

The Ionization Current
at Different Pressures and Potentials.

1. The relation between the current and the voltage was obtained for a large number of pressures. The various voltages were applied to the cylinder and thus to the electrode connected to it, and the time was taken which was required for the leaf of the electroscope to move a number of divisions equal to the range shown in Fig.2. The current in any case is proportional to the reciprocal of this time.

To illustrate the nature of the readings a few results are given in Table I.

20 Atmos.		40		140		400	
V	t	V	t	V	t	V	t
6.0	64.4	6.0	68.2	6.0	92.0	6.0	178.0
10.3	39.4	10.4	38.2	9.9	47.9	10.0	64.5
20.8	27.8	21.0	25.4	20.0	25.7	21.5	34.5
30.6	24.6	30.8	21.7	27.5	21.0	32.0	27.5
41.1	23.2	41.8	19.8	41.5	17.2	45.7	23.9
61.2	21.8	61.8	17.0	61.0	15.0	64.4	19.8
81.8	21.1	82.2	16.2	82.0	13.8	85.2	17.7
102.0	20.6	102.8	16.5	101.0	13.0	106.3	16.4
128.0	20.1	128.0	16.3	128.0	12.7	175.0	14.8
210.0	19.1	210.0	15.2	170.0	12.0	218.0	14.2
290.0	18.4	292.0	14.7	210.0	11.4	300.0	13.6
415.0	17.9	418.0	14.2	290.0	11.1	431.0	12.5
485.0	17.6	490.0	13.8	410.0	10.6	512.0	12.2
606.0	17.3	612.0	13.5	480.0	10.3	621.0	12.2
690.0	16.8	697.0	13.2	600.0	10.1	708.0	12.1
815.0	16.8	822.0	13.1	675.0	9.9	830.0	11.7
900.0	16.5	905.0	13.1	790.0	9.8	912.0	11.6
1020.0	16.5	1030.0	12.7	870.0	9.5	1040.0	11.5
				978.0	9.4		

Table I.

The results are shown graphically in Fig.3, where the abscissas represent the voltage and the ordinates the reciprocal of the time. The pressure corresponding to each curve is also given.

Fig.3.

It is noticed that the curves take the general form of the saturation curve at the pressure of one atmosphere, only that at the higher pressures, after the first rapid increase of the current, they still rise considerably with increase of voltage. In comparing with the curve for one atmosphere, it is seen that at the higher pressures the currents are considerably larger though not proportional to the pressure since at 20 atmospheres the current with 1000 volts is only about 15 times that at one atmosphere. By doubling the pressure to 40 atmospheres the current increases but 30%, and at 140 atmospheres with a pressure seven times that at 20 the current is but

1.8 times as large as at 20. Finally, at 400 atmospheres the current is less than that at 140 and not much above that at 40. With a low voltage the current at 400 atmospheres is seen to be even smaller than that at 20.

Some results which show the relation of the currents at different pressures when small voltages are applied to the electrodes are represented by the curves in Fig.4.

Fig.4.

As the pressure increases the initial slope of the curves is less. They soon rise however and up to 140 atmospheres intersect the earlier curves.

Inasmuch as the current thru the gas does not increase regularly with the density of the gas, it is of interest to plot results showing how the current varies with the pressure of the gas when the difference of potential between the electrodes is maintained at a constant value. Table II. gives some results of this kind which were obtained for a number of potentials ranging from 8.3 to 2500 volts. The initial pressure in each case was 400 atmospheres and readings were taken as the pressure was reduced by steps. The results given for the time in Table II. represent the average of from three to eight separate times obtained in seconds by means of a stop watch. The potential of the plate of the electroscope was adjusted so that the gold leaf was at zero. The watch was started the instant the key F was opened and when the leaf came to the end of the range used the watch was stopped. The following is a characteristic set and was obtained for $P = 240$ and $V = 1050$;

9.6, 9.7, 9.6, 9.4.

The current is proportional to the reciprocal of this time. Whenever a redetermination was made the results checked to well within 2% even tho the cylinder had, in the meantime,

been emptied of air and then again refilled. Likewise a similar agreement was found to exist when the current-voltage curves (i.e., curves like those shown in Fig.3) were obtained for any pressure.

V=8.3		18.7		41.5		102.0		1050		2500	
P	t	P	t	P	t	P	t	P	t	P	t
400	86.2	401	41.7	400	24.1	400	17.0	400	11.6	400	10.4
390	83.7	390	39.0	390	23.4	291	16.8	391	11.4		
380	82.5	380	38.8	382	23.4	380	16.5	380	11.4	380	10.1
370	83.7	370	38.1	370	23.0	370	16.5	370	11.1		
361	81.3			360	22.9	361	16.0	360	11.1	361	9.7
350	80.0	350	36.4	350	22.7	351	16.0	351	11.0		
340	78.7	340	36.2	341	22.1	342	15.8	340	10.7	341	9.4
331	78.1	330	35.8	331	21.1	332	15.5	330	10.6		
321	78.7	321	33.2	320	21.3	321	15.2	321	10.6	322	9.1
311	77.5	310	34.8	310	21.2	310	15.1	310	10.4		
301	75.0	300	34.1	300	20.8	301	15.0	301	10.2	301	9.1
290	75.0	291	33.7	290	20.4	290	14.7	289	10.1		
282	73.7	282	33.3	280	20.3	281	14.7	280	10.0	284	8.8
271	75.0	271	33.1	270	19.9	271	14.4	270	9.9		
261	71.2	261	32.4	260	19.9	260	14.2	261	9.7	262	8.8
251	70.0	251	31.7	250	19.3	250	14.0	250	9.6	249	8.4
240	67.5	240	31.1	240	19.0	240	13.8	240	9.6		
230	66.2	230	30.5	230	18.8	230	13.7	230	9.6	230	8.2
220	65.0	220	30.1	220	18.7	220	13.5	320	9.3	217	8.2
210	65.0	210	30.0	210	18.5	210	13.4	210	9.3		
201	62.5	200	29.2	200	18.3	200	13.4	200	9.3	201	7.9
190	61.2	190	28.7	190	18.1	193	13.2	191	9.2		
180	62.5	180	28.1	180	17.7	180	13.1	181	9.2	184	7.9
170	60.0	170	27.5	170	17.4	170	12.7	170	9.1	170	7.7
160	57.5	159	27.0	160	17.4	160	12.8	160	9.0		
150	57.5	150	26.6	150	17.2	149	12.6	149	9.0	152	7.7
140	56.2	140	25.9	140	17.2	139	12.7	140	9.1	137	7.8
127	55.0	130	25.8	130	16.8	130	12.6	130	9.1		
117	53.7	120	25.5	120	16.8	119	12.6	120	9.1	120	7.9
110	52.5	110	25.0	110	16.7	110	12.8	110	9.2		
100	51.2	100	24.7	100	16.8	99	12.9	100	9.4	98	8.2
90	50.0	87	24.7	90	16.6	89	13.1	90	9.4		
79	48.7	80	23.9	80	16.7	78	13.2	80	9.8	80	8.6
68	48.7	68	24.1	70	17.0	71	13.5	69	10.0		
58	45.0	60	24.3	60	17.4	59	14.6	57	10.8	60	9.4
50	45.0	50	24.5	50	18.1	50	14.6	50	11.1		
39	46.2	40	25.0	38	19.1	39	16.0	40	12.4	38	10.8
30	43.7	30	25.9	30	20.3	28	18.0	26	14.5		
17	43.7	20	27.7	20	22.3	19	20.2	20	16.0	20	15.0

Table II.

The results given in Table II. are shown graphically in Fig.5.

Fig.5.

As the density of the gas begins to increase there is, as was seen before, a marked increase in the number of ions produced by the rays. The number drawn to the electrodes is not, however, proportional to the density for, as the density increases, it becomes more and more difficult to collect the ions, so that the current obtained becomes a maximum at a point depending upon the

density of the gas and the potential between the electrodes. For 1050 volts the maximum is at about 150 atmospheres. With the higher potentials, for all pressures somewhat higher than those giving the maximum current, the curves are straight lines; that is, the current is an inverse linear function of the density.

At the higher potentials

The difficulty with which the ions are collected is undoubtedly due, in a large measure at least, to an initial recombination; that is, the return of a newly formed ^{electron} ion to its parent atom, the existence of which was suggested by Rutherford (Radioactivity, p.33) and by Bragg and Kleeman (Phil. Mag., Vol.11, p.466, 1906). As the difficulty with which the ions are collected increases with the density the nearness of the molecules must play an important part in this initial recombination. Since, as will be seen later, the natural recombination of the ions decreases as the density increases, it is quite probable that the currents shown in Fig.5 for the potentials 1050 and 2500 include all of the free ions produced by the rays and that the difference between

the two curves is due ^{mainly} ~~only~~ to those ions that, without the aid of the field due to the potential between the electrodes, would return to their parent atom.

The Time Required for the Rays
to Produce a Steady State.

2. When the rays begin to act upon a gas at high pressure it takes an appreciable time before the number of ions in the gas reaches a steady value, the rate of production being greater than the rate of recombination until the steady state is attained. The greater the pressure the longer is the time required.

Results illustrating this, for pressures of 200 and 400 atmospheres, are given in Fig. 6 where the ordinates are proportional to the number of ions collected after the rays have acted upon the gas an interval represented in seconds by the abscissas, the difference of potential used being 1000 volts.

Fig.6.

It will be seen that at 200 atmospheres it takes about eight seconds before the ions in the gas reach a maximum number, whereas at 400 atmospheres it requires about fourteen seconds.

The Lingering of the Ions.

3. As the density of the gas increases the readiness with which the ^{free} ions recombine diminishes to a marked extent, so that some of the ions linger for some time before they recombine. The results of some experiments on this point are shown in Fig.7.

Fig.7.

The gas was exposed to the rays for a length of time sufficient to produce the maximum number of ions. The rays were then discontinued and after a measured interval of time, 1000 volts were applied to the electrodes and the deflection of the leaf due to the charge acquired by the electrodes was measured. The deflection in this case is proportional to the charge and is represented by the ordinates in Fig.7, the time interval being represented in seconds by the abscissas. The

pressures used were 200 and 400 atmospheres. It will be seen that at 200 atmospheres an appreciable number of ions are still uncombined sixty seconds after the rays were discontinued and that at 400 atmospheres there are still uncombined ions at the end of 120 seconds.

The lingering of the ions is further illustrated by the results given in Fig. 8,

Fig. 8.

where the ordinates are proportional to the number of ions obtained at 195 atmospheres with a potential of

1090 volts, after the rays had ceased to act upon the gas for a time represented in seconds by the abscissas, the electrodes during this whole interval having the difference of potential given at the end of the curves. Thus even with a constant difference of potential of 41.5 volts acting, there are still an appreciable number of ions present after three seconds from the time the rays ceased to act.

The Time Required to Collect the Ions.

4. The slowness with which the ions are drawn to the electrodes is shown by the curve in Fig. 9, which gives the time required for the voltage to collect the ions after the rays have ceased to act, the pressure being 200 atmospheres, the potential 1000 volts and the distance between the electrodes 8 m.m.

Fig. 9.

It is seen that in this case it requires three-tenths of a second for all of the ions to get to the electrodes under a potential gradient of 1250 volts to the centimeter.

The Ionization Current at Different Temperatures.

5. An increase in the temperature of the air at high pressures causes a marked change in the ionization current, and in the number of ions collected when the rays have ceased to act and a voltage is applied to the electrodes.

Fig. 10.

In Fig.10 the ordinates of the curves shown are proportional to currents obtained at the various temperatures represented by the abscissas when the constant voltages given in each case were applied to the electrodes, the density of the gas being kept constant, the initial pressure at 20° being 200 atmospheres. With a difference of potential of about 38 volts there was

no change in the current as the temperature of the gas increased. With potentials greater than 38 volts the current increased with the temperature, and with potentials less than 38 volts, the current decreased. The amount of the change in the current per degree was greater the greater the difference between 38 volts and the potential applied.

Fig.11.

The change in the number of ions that are drawn to the electrodes at two different temperatures is shown in Fig.11. The ordinate represented by A is proportional to the number of ions drawn to the electrodes when a

difference of potential of 1000 volts was applied, one-tenth of a second after the rays ceased to act, the temperature being 21° Centigrade and the pressure of the gas 200 atmospheres. B is proportional to the number obtained four seconds after the rays ceased to act, the temperature and pressure being the same as for A. C and D are corresponding points at a temperature of 43° , the density of the gas being the same as for A and B. It is seen that more ions are drawn to the electrodes one-tenth of a second after the rays ceased to act, at the higher temperature than at the lower. After an interval of four seconds, however, the number is in this case the same at both temperatures.

This indicates that at the higher temperature a greater number of free ions are produced by the rays, and also that there is at the higher temperature a greater loss by natural recombination, as was shown by Mc Clung to be the case at densities of a lower value.

The two last above mentioned changes are opposite in their effect on the ionization current and it seems reasonable to suppose that the potential for which there is no change in the current with temperature, establishes a condition such that the increase in the number of free ions is just offset by the loss due to the increase of

the rate of recombination. At potentials less than this the time required for the ions to pass to the electrodes is greater and therefore there is a greater loss by recombination and a consequent decrease in the current. At higher potentials, however, the time is shorter so that there is a smaller loss due to recombination and therefore an increase in the current.

The indications are, however, that at 38 volts the current remains constant only for a short range of temperature and that the curve soon begins to turn downward indicating an increase in the change per degree of the rate of recombination. This will be brought out in a subsequent paper.

I have as yet made no determination of the change with temperature of the ionic velocity due to the field. A change of this kind would have no effect at the higher potentials where all the ions are drawn to the electrodes so that there is no recombination. At lower potentials it would effect somewhat the slope of the current-temperature curves. The general character of the curves shown in Fig.10 is, however, independent of a change of this kind.

-RESULTS FOR CARBON DIOXID-

The results given below were obtained with commercial carbon-dioxid, for pressures up to the liquid state. The method employed for filling the ionization chamber with carbon-dioxid was as follows: The supply cylinder containing the liquid CO_2 was inverted and placed higher than the testing cylinder. It was allowed to remain in this position for some time, so as to permit any free light impurities to rise to the top of the liquid and any heavy impurity to sink to the bottom. Before filling the ionization chamber the liquid was allowed to escape into the air for a time sufficient to force out any heavy impurity which might have collected near the outlet at the bottom of the cylinder.

-The Lingering of the Ions in Carbon-Dioxid-

1. The results for the lingering of the ions in carbon-dioxid at 61 atmospheres pressure and at a temperature of 21°C . are shown in Fig.12.

Fig.12.

Here again the ordinates are proportional to the number of ions present, at times after the rays had ceased to act which are expressed in seconds by the corresponding abscissas. The lingering is here much more marked than in air at the same pressure, doubtless owing to the greater density, the amount being comparable to that for air at 400 atmospheres.

The Ionization Current
at Different Pressures and Potentials.

2. The relation between the pressure and the current

due to the ions produced by the gamma rays was determined for a number of potentials. The results obtained for the time (t) at the various potentials and pressures are given in Table III. At the higher pressures there is an appreciable natural conductivity in the gas. This in itself gives rise to a current which is present when the rays are acting. The time for the current due to the rays alone was calculated by taking the product of the time due to the natural current alone and of the time for the two currents together and dividing this by the difference of the two times.

85		21		41.5		102		1040	
P	t	P	t	P	t	P	t	P	t
6	5.56	6	41.2	6	35.52	6	32.6	6	27.5
10		10	34.7	10	29.0	10	26.2	10	21.3
15	56.52	15	31.1	15	25.9	15	22.4	15	17.2
20		20	28.1	20	22.0	20	19.0	20	15.8
25	55.0	25	27.6	25	20.7	25	17.7	25	12.5
30	57.3	30	26.8	30	19.7	30	16.1	30	12.9
35	58.7	35	26.9	35	19.7	35	15.6	35	12.2
40	64.5	40	27.1	40	19.0	40	14.6	40	11.4
45	62.7	45	26.8	45	18.6	45	14.1	45	10.8
50	68.1	50	27.7	50	18.7	50	14.3	50	10.7
55	70.5	55	28.5	55	18.7	55	13.8	55	9.9
60	84.6	60	31.9	60	19.7	60	13.5	60	9.3
64	91.0	64	33.3	64	20.6	64	13.7	64	9.2

Table III.

These results are shown graphically in Fig.13, where the ordinates are proportional to the currents and the abscissas represent pressures up to 65 atmospheres.

Fig.13.

Up to the pressure at which the gas liquefies the curves are in general similar to those for air. This indicates that the ionization is independent in a large measure at

least of the intermolecular forces present, even when the gas approaches the liquid state.

The Natural Conductivity of Carbon Dioxid.

3. In Fig.13 the curve B represents the current due to the natural conductivity of the CO_2 , the difference of potential being 1000 volts. The first portion of the curve from a to c shows how the natural conductivity increases as the gas approaches the liquid state. There is a very sudden increase (cd) in the conductivity at 62.5 atmospheres which is the pressure at which the CO_2 liquefies for the temperature involved; namely, 22.6°C . At this stage when the cylinder had become filled with the liquid the lower valve was closed so that the density could not change. Heat was then applied to the outside of the cylinder and readings for the current were taken as the temperature slowly increased. The results are shown by the portion "def" of curve B, where now the abscissas represent temperatures instead of pressures and where the ordinates are proportional to the current due to the natural conductivity. It is seen that the conductivity

increases slowly with the rise in temperature up to about 33° C., above which however it diminishes rapidly.

The Ionization Current at Different Temperatures.

4. The ionization current due to the rays was also obtained in this range of temperature, the density remaining constant. It undergoes no marked change as is shown by the extended portion of the current pressure curve at 1070 volts, the current increasing slowly with the rise in temperature. The fluctuating of the readings was due to inaccuracy in measuring the short time interval (about two seconds) required for the leaf of the electroscope to move through the range used, the available capacity being too small. This shows that the ionization due to the rays is, at least for the sensibility and potential involved in this investigation, quite independent of the natural dissociation to which the liquid or vapor conductivity is due.

-SUMMARY AND CONCLUSIONS-

The results obtained in this investigation and the conclusions drawn from them are as follows:

(a)- As the density of air or CO_2 increases, the ionization current attains a maximum value. The higher the potential the greater is the value of the density giving the maximum current. At potentials higher than 100 volts the current, beyond the maximum point, is an inverse linear function of the density. A probable explanation of these results is that when the molecules are closer together it becomes more difficult for an ion to leave its parent atom.

~~(b) The velocity of the ions, under a given potential gradient, is less the greater the density. This is undoubtedly due to the influence of the adjacent molecules.~~

(b)- It requires several seconds at the higher densities for the rays to produce a steady state, indicating that a proportionately smaller number of free ions are produced.

(c)- When the density of a gas increases the ions linger for a longer time before they recombine, showing that after an ion becomes free it is more difficult for it to combine with another ion when the density of the

gas is considerable.

(d)- The rate of recombination of the ions increases as the temperature of the gas increases.

(e)- The number of free ions produced by the rays increases with the temperature.

(f)- The natural conductivity of CO_2 gas increases as the gas approaches the liquefying pressure. When the gas liquefies its conductivity suddenly changes to more than double its former value.

(g)- The natural conductivity of liquid CO_2 decreases slowly with increasing temperature up to about the critical temperature when it begins to decrease rapidly.

(h)- The ionization produced by the rays is quite independent of the changes CO_2 undergoes when it liquefies and when it passes thru the critical temperature and pressure.

In conclusion I wish to express my sincere thanks to Dr. John Zeleny for many helpful suggestions and to Dean F. S. Jones for kindly securing for me the necessary apparatus.

Biographical Sketch.

Henry Anton Erikson was born July 30, 1869, in Mt. Morris, Waushara Co. Wisconsin. He prepared for the university at Willmar Seminary and at the Northern Indiana Normal. He entered the University of Minnesota at the beginning of the school year 1893-4 and graduated from the course in electrical engineering at the close of the year 1895-6. After graduating he taught one year in the High School of Rochester, Minnesota and then returned to the University of Minnesota as instructor of physics, which position he held until 1905 when he was made assistant professor of physics in the same department.

Preparatory to the receiving of the Doctors Degree he presents as a minor a two years study of Differential and Integral calculus as presented by Todhunter and Differential equations as presented by W. W. Johnson, all taken under the instruction of Dean H. T. Eddy.

As a second minor he presents a two years study of the Theory of Electricity and Magnetism as presented by

Arthur Gordon Webster, the work being pursued under the direction of Dean Eddy.

As a major he presents two lines of study, one in experimental physics and the other in theoretical physics and astronomy.

In experimental physics he presents a two years study of contact, potential and surface layers, and a two years study of the ionization of gases and liquids, all pursued under the direction of Dr. John Zeleny.

In theoretical physics and astronomy he offers the following as studies pursued in class:

Least squares.

Practical Astronomy (Transit work)

Oppolzer's Bahnbestimmung.

Routh's Rigid Dynamics.

Webster's Dynamics.

M^cYer's Kinetic Theory of Gases.

Lectures on Molecular Physics taken at the University of Chicago.

Pupins Wave Propagation.

Drudes'. Optics.

The time equivalent of the above major and minors
is fourteen and one half years.