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DETERMINATION OF THE CHARGE OF AN ELECTRON BY WILSON'S METHOD, USING RADIUM.

BY L. BEGEMAN.

The following discussion of the experimental determination of the charge e of an electron may prove interesting inasmuch as the conditions of the experiment were in many respects more favorable than those of previous attempts. As is generally known, determinations of c have been made by J. J. Thomson and H. A. Wilson at the Cavendish-laboratory, England. Their methods were quite different, although both obtained their data from observations of ionized clouds produced by the rapid expansion of supersaturated air in a fog chamber.

A description of the apparatus employed by J. J. Thomson will be found in his work entitled "Conductivity of Electricity Thru Gases," 1906 edition; also in the Phil. Mag., Vol. 5, page 346. To secure a constant source of radiation J. J. Thomson used radium instead of X-rays. The radium was suspended at a given distance above the fog chamber and maintained continuously in the same position during the observations. C. T. R. Wilson's device for rapid expansions was used to produce the clouds in the fog chamber. The clouds were produced between two plane electrodes maintained at a constant difference of potential. Now if n is the number of droplets in the cloud and e the charge on each, then the total charge of the cloud will be $n\ e$. Furthermore, if u is the mean velocity of the positive and negative ions in a given electric field, then the current thru unit area of the ionized gas in the field will be $n\ e\ u$. Hence, it is only necessary to measure the current u to determine the value of $n\ e$. Thomson used the method of Zeleny and Rutherford to get the value of u; i. e., the velocity of ions in a field of known strength. The method of C. T. R. Wilson was used to determine the number of particles of water vapor in a unit volume of the cloud. Knowing the current velocity and the number of particles it is a simple calculation to determine e the charge of an electron. J. J. Thomson's average determination gives the value of e as 3.4x10-10 E. S. units.

In the light of more recent investigations of ionized cloud phenomena, J. J. Thomson's determination is certainly open to serious criticism. For instance, he states that when the expansion is greater than 1.31, positive as well as negative ions are caught, and that the number is about twice as many as is obtained at expansions varying from 1.27 to 1.29. He says also that when the expansion is greater than 1.33, the number of nuclei caught by the cloud does not depend upon the amount of the expansion. We understand that Thomson's observations were all taken at an expansion of about 1.33, where he assumed that every droplet in the cloud carried but one ion either positive or negative. In this assumption we see the probable error of his work.

According to Carl Barus in the May publication of the Carnegie Institute entitled "The Condensation of Vapor Induced by Nuclei and Ions," the nucleation induced by radium increases rapidly with increasing expansions from 1.33 to 1.4. Above 1.4 the nucleation gradually increases and a maximum is not attained until the dp. is 34 cm. (dp. is the difference of pressure between that in the fog chamber after expansion and the ordinary atmospheric pressure. A dp. of 34 cm. corresponds to an expansion of 1.7.) Fig. 1 is a graph by Barns showing the nucleation due to radium at various pressures. In this graph the ordinates represent the nucleation (the number of condensed particles per cubic centimeter in the cloud in units of 1000); while the abcissae represent the dp. in centimeters. As will be noted, the nucleation begins at a dp. of 19 cm. and gradually approaches a maximum after a dp. of 22 cm. is reached. Now if Barus' observations are correct then J. J. Thomson's assumption that every water particle in the cloud at an expansion of 1.33 carries a single ion can hardly be accepted since such a result would only be likely at expansions giving the maximum nucleations. Barus observed that at the lower expansions nuclei carried a variable number of ions. My own determinations at an expansion of 1.33 also indicate this fact.

Fig. 2 shows a curve very similar to Barus', but one which was obtained in an entirely different manner. In this figure the ordinates give the time it took for the cloud formed in the fog chamber by expansion to fall a distance of 2 millimeters under the action of gravity. It will be seen that as dp. increased from 16 cm. to 24 cm. the time increased from 3 second to 5.2 second. At the low expansion the droplets were heavy, falling rapidly. As the dp. increased the droplets became smaller with a corresponding diminished velocity. The density of the clouds also increased enormously with the high pressures. Comparing the curve of figure 2 with that of Barus in figure 1, we note that the velocity of an ionized cloud under the action of gravity varies, approximately, inversely as the nucleation.

An account of H. A. Wilson's method of determining *e* in the Phil. Mag., Series 6, Vol. 5, 1903, page 425. The method has the advantage over J. J. Thomson's in that it is not necessary to know the number of particles in the ionized cloud. All that one needs to know is, first, the velocity of the cloud under the action of gravity, and, second, the increased velocity under the combined action of gravity and a static field of known strength. For instance, if the force of the static field is X and the charge of the particles in the cloud is *e*, then the total force acting when the field is on is equal to $mg + xe$; where m is the mass of each particle. When the field is not on, the force acting is mg. Since the rate of uniform motion of a sphere in a viscous fluid is proportional to the force acting, we have:

$$\frac{mg}{mg+xe} = \frac{V_0}{V_1}$$

$$\text{Solving } e = 3.1 \times 10^{-9} \ \frac{g}{x} \ (V_1 - V_0) \ V_0^{1/2}$$

$$\text{And } m = 3.1 \times 10^{-9} \times V_0^{\frac{3}{2}}$$

Wilson's determinations varied from $2x10^{-10}$ to $4x10^{-10}$ and his average was $3.1x10^{-10}$. All of his determinations were taken at a dp. of 17 cm.

The correctness of Wilson's result might be questioned for several reasons. First, he used X-rays as his ionizing source, which we know may be extremely variable. It is probable that this lack of uniformity of X-rays as an ionizing source accounts for the marked differences in the velocities of his clouds for successive observations. In a series of eleven sets of observations we find that the timing of his clouds varies from 12 seconds for a distance of 5 millimeters to 33 seconds for a distance of 5 millimeters. In my own work with radium as a source of ionization, the timing of the clouds, as will be observed from data later, was practically constant for any given difference of pressure.

Again, as has been stated above, Wilson worked at a dp. of 17 cm., which, according to Barus, is right within the region of persistent nuclei. Barus observes that these persistent nuclei induced by X-rays are ionized, carrying a variable number of ions; one, two or three, perhaps. He notes also that their number in the fog chamber varies with the time of exposure and also with distance of the X-ray bulb from the fog chamber. Their masses, accordingly, vary considerably, which no doubt accounts for the different layers witnessed by Wilson in his clouds. A serious objection to Wilson's work is seen in the fact that the number of persistent nuclei vary with the time of exposure. If the time of exposure was not the same in all determinations his velocities would necessarily vary considerably, as his data shows. X-rays were first used as the ionizing source for the determination of *e* at the Ryerson laboratory, but the results were so unsatisfactory that radium was substituted.

The data for the determination of *e* given in this paper were obtained under conditions which preclude in a measure the criticisms on Wilson and Thomson. A one per cent compound of radium was used as the ionizing source. Barus shows conclusively in his experiments that the gamma rays of radium are the source of nucleation in the fog chamber. These rays are productive of fleeting nuclei or ions and not of the persistent type arising from X-rays described above. Of course, the persistent type of a dust-like nature would still occur, even with radium, where the air is not filtered, as was the case in these experiments. As was stated above, the X-ray persistent type are cumulative with the time of exposure. This cumulative effect, accordingly, does not occur with radium and any slight variation in the time of exposure between observations would not be a source of error.

All observations were taken at dp. varying from 22 cm. to 24 cm., which it will be observed, is well within the region of maximum nucleation as given by Barus for an expansion apparatus that is subject to some resistance, as is the case of the Wilson type. During successive observations the radium was continuously kept in position very close to the fog chamber. The nucleation within the fog chamber was very uniform. This was evident from the fact that the coronnas due to the beam of light penetrating the fog chamber were of uniform width throughout their extent. The surfaces of the clouds were usually sharply defined, permitting good time observations.

Although the apparatus used was entirely different from that of Barus, yet in the course of the work all of the phenomena of nucleation described by Barus were experienced and renderd familiar. The velocity of the dust-like persistent nuclei were frequently timed at dps. varying from 16 cm. to 18 cm. These velocities were usually found to be about five to six seconds for a distance of five millimeters, showing that their masses were relatively large. The radium, of course, was not in place in timing the persistent nuclei. With radium in place denser clouds made up of smaller particles were obtained at a dp. as low as 16 cm. Furthermore, the particles in these clouds were ionized, negatively charged, since their falling velocities were markedly increased when the electrodes between which the cloud was produced were charged. In all observations with a field the upper electrode was charged negatively and the lower positively. As the dp. for the expansions gradually increased the velocities of the clouds diminished, as is shown in fig. 2. At dps. from 22 cm. to 24 cm. a practically constant velocity was attained which was invariably between 5 and 6 seconds for a distance of 2 millimeters. It was because of this constant velocity that all observations for the determination of *e* were taken at these differences of pressures. It is very probable that at these expansions practically all of the droplets carried but one ion.

It might be interesting to note further that on several occasions while expanding at as high a difference of pressure as could be attained with apparatus, colloidal clouds were distinctly observed. These clouds consisted of very minute particles, as was evident from the fact that their falling velocities were very slow. In timing them it was found that it required 15 to 18 seconds for the surface of the cloud to fall through a distance of two millimeters. This indicates that the droplets of the colloidal nuclei are three to four times smaller than those of the fleeting nuclei. Barus' pamphlet did not come to my hands until the close of work and I was much impressed with the coincidence of phenomena observed under such different conditions.

Below is given a series of preliminary determinations of *e* taken during the first weeks of the work. The mechanism used for producing the expansions in the fog chamber and for throwing on the battery terminals to charge the field was crudely mechanical, so that the conditions of the successive observations could only be duplicated in a rough way. In taking these observations Wilson's method was followed. First, successive expansions were produced to get rid of the dust-like persistent nuclei. These were followed by two observations with the radium in place, one with the field off and the other with the field on.

Each determination represents the average of a series of eight to ten alternate readings taken in the manner described. The calculations were made by means of Wilson's equation. The difference of potential between the electrodes of the fog chamber was in every case supplied by a storage battery of 1600 volts.

3.87×10^{-10} E. S. Units
4.65 " " "
3.82 " " "
4.10 " " "
4.20 " " "
3.64 " " "
4.27 " " "
4.43 " " "
3.73 " " "
4.03 " " "
4.55 " " "
4.40 " " "

Mean 4.14×10^{-10} E. S. Units

The data which follow were obtained under decidedly improved conditions of the apparatus. The mechanical device for producing the expansions was discarded and electrical contrivances were substituted so that by the closing of a key the expansion in the fog chamber could be produced—instantly followed, when desired, by the connection of the poles of the storage battery with the electrodes. The method of observation were also slightly changed. Some were taken by what might be termed a group method. First, one or two expansions were produced to get rid of the persistent nuclei. These were followed by three observations without the field and then by three with the field. The times between the different observations were as nearly equal as could be obtained by a single experimenter under the conditions of work. It is not likely that the small differences of the intervals affected the results to any extent. By making the observations rapidly so that compressions in the fog chamber would quickly follow the expansions it was frequently possible to take as many as six or eight observations before any diminution of the supersaturation in the fog chamber became apparent.

About one-half of the observations were taken by grouping alternate readings. After expansions to get rid of persistent nuclei a series of four to six alternate readings were taken in succession. The results of the two methods were practically the same as indicated by the data.

On examining the data it will be found that the velocity of the cloud with the field off is practically the same in every case. It will also be noted that the difference between the velocities with the field off and field on varies directly as the voltage. When the voltage is double the difference is approximately double. We should expect this since the velocity due to gravity is always the same.

During all observations the distance between the electrodes in the fog chamber was invariably 5 millimeters. The timing of the clouds, however, was taken through only a distance of 2 millimeters. This was necessary for several reasons. By timing through a short distance the error due to evaporation would be small. Again, it was found on expansions that the upper electrode, the terminal of which passed through a rubber stopper, would project the surface of the cloud, giving it an accelerated motion which it would maintain for a distance of approximately two millimeters. All observations were made with a micrometer microscope adjusted to a cathetometer support. Owing to the projection due to the electrodes it was found necessary to bring the first cross hair of the microscope near the middle of the space between the electrodes so as to get the time of the cloud when moving at a uniform speed.

One of the greatest difficulties encountered in timing the clouds, especially when high voltages were used, was the breaking up of the sharply defined surface of the cloud by the action of field. Under the circumstances it was frequently impossible to time the surface cloud for the second cross hair of the microscope. When 3000 volts were used the surface of the cloud on approaching the positively charged electrode would exhibit a phenomena somewhat analogous to the scintillations that take place inside of the spinthariscope. Particles would be projected upward in all directions, giving the cloud a hazy appearance. As a rule the main body of the cloud could be seen descending toward the positively charged electrode, while the scintillations were taking place. The best observations for the velocity determinations of the clouds were obtained at voltages varying from 2000 to 2400 volts. The electrodes in every case were charged with a storage battery of 1600 cells, which enabled a variation of the static field. All time observations were taken with a stop watch. The temperatures given with some of the determination have reference to the room in which the experiment was conducted. For two or three days in November the heating was not good in the laboratory, the temperature maintained being about18°C. At that temperature it was found impossible to get well defined clouds for observation. An electric heater was brought into service and the temperature was brought to 23°C, when good clouds were again obtained. After that the temperature of the room was taken with each series of observations. Owing to space the complete data for only two determinations are given to show how they ran:

Field 2,400 volts=16 E. S.
V_0=.0387 cm.
V_1=.0497 cm.
Temp.=26°C
e=4.1×10^{-10}

Field off	Field on
5.4 secs.	4.0 secs.
5.2	4.0
5.2	4.0
5.0	3.8
5.0	4.4
5.4	4.0
5.2	4.0
4.8	4.2
5.4	4.4
5.2	3.6
5.2	4.0
5.2	4.0
5.0	3.8
Mean 5.17	4.02

Field 2,950 volts=19.67 E. S.
V_0=.0387 cm.
V_1=.053 cm.
Temp.=26°C
e=4.25×10^{-10}

Field off	Field on
5.2	3.8
4.8	3.8
4.8	3.6
5.2	4.0
5.6	4.0
5.6	4.0
4.8	3.2
5.2	4.0
5.2	4.0
5.2	3.6
5.2	3.6
5.2	3.6
Mean 5.17	3.77

Summary:
3.81×10^{-10}
3.89
4.10
4.25
4.34
3.66
4.10
3.94
4.37
3.84
Mean 4.03×10^{-10} E. S. Units

Since the charge of the hydrogen atom is the same as the negative ion, the above determination gives on computation a mass of 1.3x10^{-24} for an atom of hydrogen and a mass of 2.6x10^{-24} for a molecule or hydrogen. Taking the mass of a cubic centimeter of hydrogen at 0°C. and 760 mm. as 9x10^{-5} grams we get for N the number of molecules per cubic centimeter, 3.4x10^{-19}. This is lower than Wilson's or Thomson's determination, but nearer the best estimates according to the kinetic theory of gases, which I find to be as low as 2.1x10^{-19}.

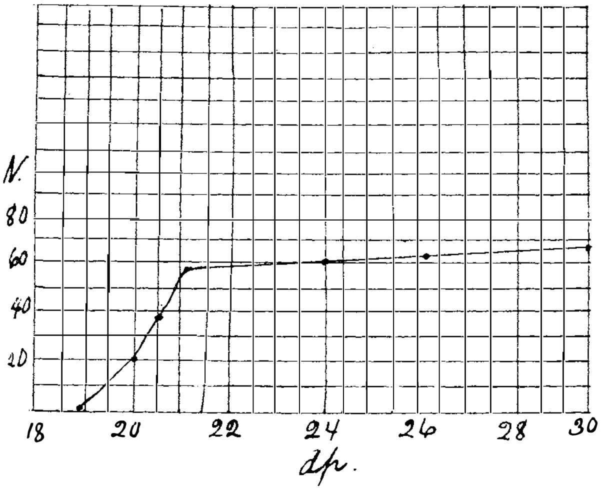

Fig. 1

Determination of the Charge of an Electron—Begeman.

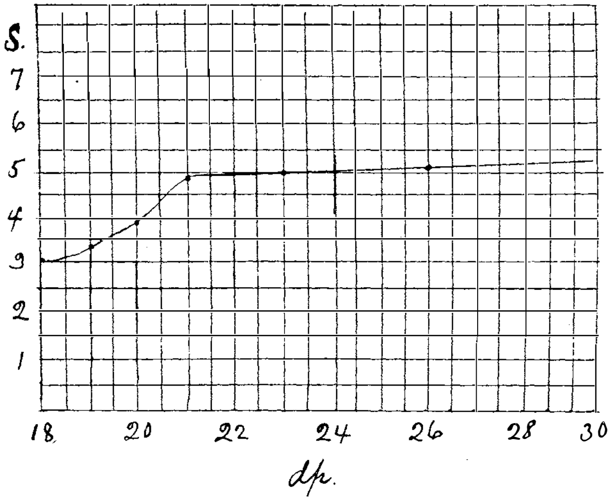

Fig. 2.

Determination of the Charge of an Electron—Begeman.