CONDUCTION OF ELECTRICITY THROUGH GASES AND RADIO-ACTIVITY

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A TEXT-BOOK WITH EXPERIMENTS

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With 78 Illustrations

PREFACE.

The subject treated in the present volume is one which has had a remarkably rapid growth. Its wonderful development has taken place within a comparatively few years and consequently up to the present the study of it has been confined almost entirely to the realm of research. The fundamentals of the subject however have now been pretty thoroughly investigated and placed on a somewhat definite working basis and it is felt that it has reached the stage when it may with advantage be introduced, to some extent, into the regular lecture and laboratory courses of the colleges. The investigations in the subject of gaseous ionization in general have increased our knowledge of physical phenomena, especially in connection with electricity, to such a marked degree and have attracted such wide-spread attention that we believe every student of physics ought to have at least some knowledge of the facts in this connection. Since, as far as we know, there did not exist what may be called any regular college text-book on the subject, or manual describing an experimental course, suitable for the less advanced student or undergraduate, the present text-book was undertaken. We therefore hope that it may find a place and fill a growing need in a comparatively new field.

Owing to the existing conditions in connection with the subject, the plan of a combined text-book and laboratory manual has been adopted as one which seemed to be most useful to the student in general. Our aim has been to present in simple form the fundamental facts and explanatory theories accompanied, where possible, by the description of suitable experiments to be performed in the laboratory so as to enable the average student to gain a working knowledge of the main facts and principles of the subject without going too much into details, and to form for those wishing to continue the work a basis for more advanced study and original research if desired.

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In most cases the results to be expected from the experiments are given so that the student may know what to look for, as in this class of experiments, probably more than in almost any other, the inexperienced are apt to be led astray by erroneous results which arise from incorrect manipulation or want of proper precautions. In addition, this plan allows the book to be used as an ordinary text-book without actually performing the experiments, if so desired.

To aid in selecting the experiments from the rest of the text a complete list of them is given at the beginning of the book and the more difficult ones are indicated therein. The latter experiments may with advantage be omitted from an elementary first course. Even in the case of the more elementary experiments in a great many instances they do not necessarily depend upon the preceding ones and consequently the instructor may easily make a selection, without breaking the continuity, to fill the needs of a class requiring a shorter course.

As the methods required in the experiments in this class of work are different from those of any other and a large portion of the apparatus has to be specially made, the descriptions of methods and apparatus have been given in some detail and a lengthy chapter, namely Chapter II, has been devoted to general descriptions along this line. In this connection we have also had in mind research students beginning this type of work as it is found that they usually encounter difficulties of this particular nature at the outset.

On account of the continual development of the subject numerical values of constants, etc., frequently suffer change owing to improved methods of determination. In these cases an endeavor has been made to give such values as are generally accepted at the present date.

My thanks are due to Mr. G. Dunn, of the Physics Building in McGill University for kind assistance in preparing some photographs for illustration.

R. K. McClung.

Winnipeg, Man.,
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LIST OF EXPERIMENTS.[1]

PART I.

[1] The experiments in italics are of a more difficult nature than the others and may with advantage be omitted in selecting an elementary or first course. They may be reserved until some experience has been gained in the use of the special apparatus and methods by means of the simpler experiments.

PART II.

PART I.

CONDUCTION OF ELECTRICITY THROUGH GASES.

CHAPTER I.

INTRODUCTORY EXPERIMENTS ON ELECTRIC DISCHARGE.

1. **Introduction.**—Ordinary gases under normal conditions are practically non-conductors of electricity. When however a difference of potential is established between two points in a gas a state of strain exists in the gas which increases with increase of potential until the gas, no longer able to withstand the strain, breaks down and a discharge of electricity passes between the points, either in the form of a brush discharge or a more violent disruptive spark. The potential necessary to cause such a discharge is comparatively high, several thousand volts being required to produce a spark of one centimeter length in air at atmospheric pressure. The potential required depends upon the nature and the pressure of the gas and the shape of the electrodes. As the ordinary spark discharge forms a connecting link between the general subject of electricity (with which all who read this are supposed to be familiar) and the more particular one of the conduction of electricity through gases, and since the effect of gas pressure on this discharge has played such an important part in the development of our subject, we will begin with a few introductory experiments thereon.

2. **Brush Discharge.**—Attach a pair of combs, consisting of a set of sharp needle points as shown in Fig. 1, to the poles of either a Wimshurst machine without any Leyden jars, or an induction coil. Excite the Wimshurst machine or induc-

tion coil and observe in a darkened room the glow surrounding these points in the air. Observe the increase of this glow or brush discharge with increase of voltage.
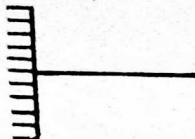
3. Spark Discharge from Induction Coil. —An induction coil capable of giving a maximum spark of from 25 to 30 cm. will be found suitable for these experiments, although a slightly smaller one will serve the purpose.

Fig. 1.

(*a*) In a darkened room cause a spark to pass between the terminals, either pointed or spherical, of the secondary of the induction coil. Adjust the current in the primary and, starting with a spark length of a centimeter or two, gradually increase the spark gap and observe carefully the nature of the spark produced in air at the various stages. Observe the irregularity of path as the length increases.

(*b*) Closing the make-and-break attachment of the induction coil pass an alternating current through the primary and observe carefully the nature of the discharge between the terminals of the secondary. Compare this discharge with that obtained from the direct current and observe carefully the difference.

4. Relation Between Length of Spark and Potential.—To determine experimentally the relation between the length of a spark in air and the minimum potential necessary to produce it, the following apparatus will be found convenient: (1) A small two-plate Wimshurst influence machine having plates 35 to 40 cm. in diameter; (2) a battery of eight or ten Leyden jars, each of a capacity of about 1500 electrostatic units; (3) an electrostatic voltmeter with range extending from 200 or 300 volts to about 30,000 volts; (4) an adjustable spark gap with spherical terminals mounted so that the distance between them may be adjusted and determined accurately by means of a fine screw adjustment. Connect the different parts of the apparatus together as indicated in Fig. 2. See that the terminals of the spark gap are clean and well polished. After the passage of each spark repolish them with a piece of cham-

ois leather, as the spark destroys the polished surface at the point where it passes. Keep the terminals also free from dust or moisture. Place the terminals of the spark gap in contact.

TERMINALS OF WIMSHURST
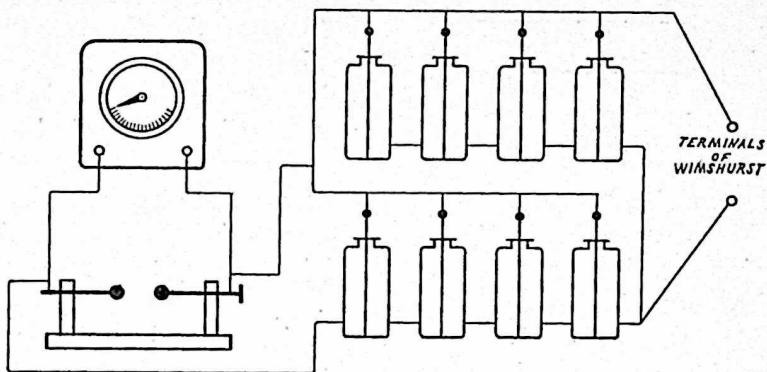
FIG. 2.

This may be determined with certainty by observing the voltmeter, for it will read zero even when the Wimshurst machine is working if the spheres are in contact, since there is no potential difference between them. Separate the terminals a small fraction of a millimeter and very slowly turn the influence machine and carefully watch the movement of the voltmeter needle until it suddenly returns to zero when a spark has passed. Observe this maximum reading of the voltmeter and also the length of spark gap as indicated by the screw attachment. Gradually increase the length of spark gap by small stages and observe the potential necessary to produce a spark in each case. Then plot a curve having lengths in centimeters for abscissæ and corresponding voltages for ordinates.

5. **Effect of Pressure on the Electric Discharge.**—The pressure of the gas has a very marked effect on the appearance and nature of the electric discharge through it. To study this the discharge must take place within an air-tight glass vessel. A glass discharge tube suited to this purpose is represented in Fig. 3. This consists of a straight glass tube about 4 cm.

in diameter and from 30 to 40 cm. in length into the ends of which platinum electrodes are sealed, and to these are attached metal disks. Aluminium disks are very suitable. To the side tube, a, connect an air pump and a manometer to measure the pressure within the tube. Connect the electrodes to the terminals of a Wimshurst machine or an induction coil. Gradually lower the pressure and carefully
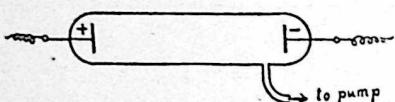
Fig. 3.

observe the change in appearance of the discharge within the tube as the pressure changes. Observe also, by means of a voltmeter, the diminution in potential necessary to produce the discharge with decrease of pressure.

At first the spark becomes more regular and uniform between the electrodes, then broadens out and assumes a fuzzy appearance of a bluish color. Observe carefully the marked appearance of the discharge when a pressure of about half a millimeter is reached. The negative electrode or cathode will be found to be covered with a thin layer of luminosity; next to this will be a dark space which is called the Crookes dark space; immediately beyond this will be a luminous part called the negative glow, and beyond this again a second dark region sometimes called the Faraday dark space. The luminous region between this point and the positive electrode or anode is called the positive column. If the pressure at this stage be adjusted slightly over a very small range and also if the current through the tube be varied slightly the positive column will divide up into alternate light and dark spaces which are called striæ. The appearance of these striæ depends on a variety of conditions of pressure, current, size of tube, nature of gas, etc.

If the discharge be made to pass for any length of time through the tube the gas pressure will increase slightly. This will be especially marked in the case of a new tube which has not been used much before. This is due to the escape of the occluded gas from the walls and electrodes. Repeat these

experiments, using other gases in the discharge tube and compare the results with those obtained for air.

6. Effect of Altering the Position of the Anode.—Repeat these experiments, using a discharge tube similar to the above only of greater length, about 80 to 100 cm., and having an adjustable anode so that the distance between the electrodes may be varied. Such a tube is shown in Fig. 4. The anode consists of two aluminium disks, fastened together by a central aluminium rod and fitting loosely in the tube so that it may
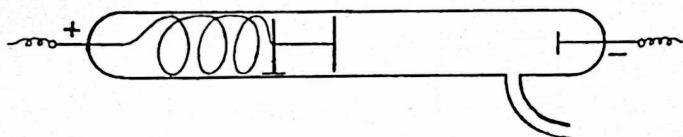
FIG. 4.

slide along inside the tube. Attached to the bottom is a piece of soft iron so that the anode may be moved along the tube by means of a magnet from the outside. The anode is connected to the platinum wire at the end of the tube by means of a very light flexible coil of wire which simply makes connection but is not strong enough to move the anode.

Observe the relative proportions of the space between the electrodes occupied by the different sections of the discharge for different distances between the electrodes. Note that when the distance between the electrodes is greater than a few centimeters an increase of distance does not cause any increase in length of the negative glow or dark space, but the increase takes place entirely in the positive column.

Using a discharge tube of the form shown in Fig. 5 in which the anode is placed in a side tube instead of in a direct line with the cathode, observe the appearance of the discharge at the pressure of about half a millimeter. Note how the positive column bends into the side tube but the position of the negative glow does not alter. If the side tube is not too far from the cathode and the pressure be lowered somewhat the negative glow may even extend in a straight line beyond this side tube.

7. Cathode Rays.—Using the tube shown in Fig. 5 lower the pressure still more and carefully observe the change of appearance until, in the neighborhood of one hundredth of a millimeter, a new phenomenon makes its appearance. The positive column will begin to disappear and a light phosphorescence will make its appearance on the walls of the tube. The color of this phosphorescence will depend upon the nature of the glass; if the tube is made of ordinary soda glass the phosphorescence will be of a greenish yellow color, while in the case of lead glass the color will be blue. This phosphorescence appears to be produced by streams of very minute particles issuing normally in straight lines from the cathode. They are consequently called cathode rays and have remarkable properties. These properties will be discussed in Chapter III.
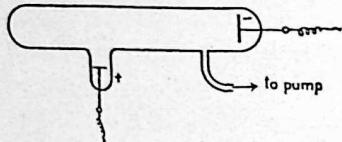
FIG. 5.

CHAPTER II.

APPARATUS AND GENERAL METHODS.

8. The study of the conduction of electricity through gases and radio-activity during the last few years has developed a particular class of measuring instruments and methods of measurement particularly suited to this class of work. The instruments which are used in this branch of physics were, for the most part, well known in principle long before the question of conductivity in gases was studied, but within the last few years they have reached a much higher state of perfection and utility. As some of these instruments and the methods of measurement used in this subject present many peculiarities—sometimes of a rather troublesome nature—which one does not find in any other class of physical measurements in the laboratory and which are not usually given in text-books on the subject, nor even in the original papers, and which often occasion considerable trouble and loss of time to one beginning the subject, a somewhat detailed description of apparatus and general methods of procedure will be given in this chapter.

9. Small Accumulators.—One of the most necessary parts of the equipment for this work is a perfectly reliable source of potential which may be adjusted at will from a few volts to six or eight hundred volts. This range will serve for most purposes, although it will be found convenient in some cases if the range can be extended to a thousand volts. This steady potential is best obtained from a set of small accumulators. Since the current to be drawn from this steady voltage is never, except in very rare cases, more

Fig. 5a.

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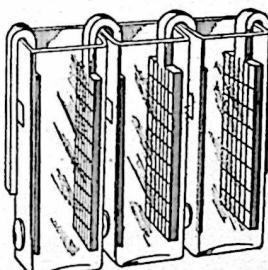
than a very small fraction of an ampere, the storage cells used to furnish it need not be of large capacity. They are identical in principle with the ordinary large accumulators and are usually made of plates of about 18 to 20 sq. cm. in area contained in correspondingly small glass vessels. There are different varieties of these small cells furnished by different makers. One very convenient type is shown in Fig. 5a on the preceding page.

These cells should be set up in wooden trays, lined with insulating material such as mica, in small lots in series of not more than ten or twelve, with their terminals connected to metal mercury cups, and these separate lots may be combined in larger trays so that any number may be readily connected temporarily in series as desired.

The care of these cells is a very important factor in gaining efficient service from them. They should be kept in a closed cabinet to preserve them free from dirt, but this cabinet should be so arranged that each small lot can be separately disconnected and removed so as to be attended to individually, as connections and individual cells are very apt to go wrong through corroding, breaking and other causes. Lead wires covered with rubber are usually more satisfactory as permanent connectors than copper or other metal. The cells should be kept clean and well insulated. They should be kept charged up to their full voltage and never under any circumstances should sufficient current be drawn from them to cause them to fall more than 12 or 15 per cent. below their normal voltage before recharging. They ought to be charged regularly, and even when they are not used for a considerable length of time it is advisable to discharge them slowly through a suitable resistance at intervals and recharge them again during the time they are idle. Care should be taken to charge them at the proper rate, as too large a charging current is apt to injure them. The charging rate is usually furnished by the makers with each particular type of cell.

Since the voltage used in most cases is quite large, extreme care should be taken to prevent a short circuit of the cells, as

such of course is injurious to the cells and may be disastrous to other valuable apparatus involved.

If these precautions are observed and the cells given careful attention they should present no difficulties.

10. **Quadrant Electrometer.**—In most text-books, even of a somewhat advanced nature, the quadrant electrometer is usually dismissed with a more or less brief description and consequently is not as well known in detail as it might be. It is also somewhat neglected in many laboratory courses. As the use of the instrument is so extensive and important in the class of work in hand, and as it has the reputation, not wholly undeserved, of being a difficult and troublesome instrument to use, a somewhat detailed account will be given here.

The electrometer consists of the following essential parts which are common to every type: A circular metal box, fixed in a horizontal position and having a small vertical central hole through it, is divided by very narrow saw cuts into four quadrants as indicated in Fig. 6. Each of these quadrants rests on an insulating support. Within these quadrants, midway between the upper and lower plates, is suspended by a very light fiber suspension a flat dumbbell-shaped needle made of aluminium or other light conducting substance. The diagonally opposite quadrants are connected together as shown in Fig. 6. If the needle is hung symmetrically with regard to the quadrants as shown in the diagram, and if it is charged to a positive potential and a difference of potential be established between the two pairs of

FIG. 6.

quadrants, the needle will be attracted by one pair and repelled by the other pair and will rotate in a horizontal plane. The amount of attraction and repulsion will depend upon the difference of potential between the quadrants and the potential of the needle and consequently the amount of rotation of the
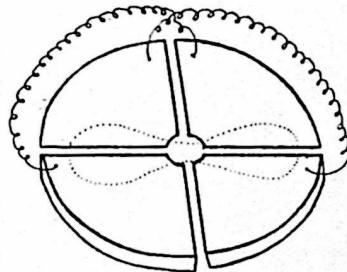
needle will depend upon these factors and also upon the torsional rigidity of the suspension.

The remaining parts vary in different types of instruments. In the older forms and even in some of the modern types of instrument the needle is connected to a small condenser usually in the form of a Leyden jar to increase the capacity of the needle, so that any small leakage of the charge from the needle will not alter its potential as much as if its capacity were small. Connection between the needle and inside coating of the Leyden jar is made by allowing the central rod of the needle to extend below the quadrants and dip into sulphuric acid contained in the Leyden jar. The acid also acts as a drying
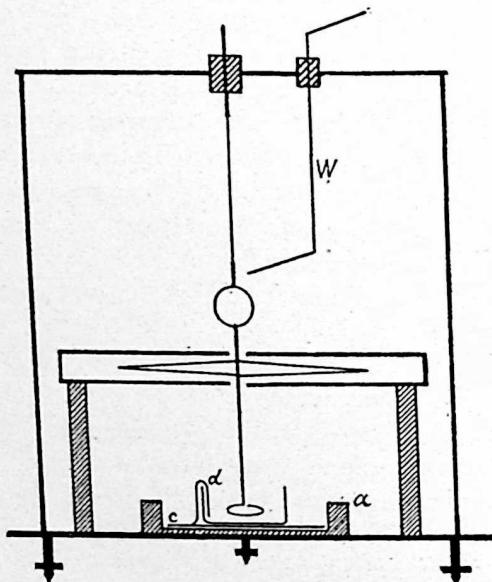
FIG. 7.

agent to keep the instrument free from moisture. If the wire dipping into the acid is bent into a small loop as shown in Fig. 7 the acid also serves to damp the motion of the needle so that it may turn more slowly and at a uniform speed when the quadrants are receiving a charge at a uniform rate.

There are difficulties connected with this Leyden jar. It is very difficult to secure perfect insulation between the coatings for large charges on the needle and its potential does not therefore remain constant, which is a serious drawback in accurate measurements. A more satisfactory form of condenser, devised by Strutt and shown in Fig. 7, in which the dielectric is ebonite or sulphur—which are much better insulators than glass—may be used. A circular plate of ebonite about 1 cm. thick and 6 or 7 cm. in diameter is recessed until the central part is only about 0.5 mm. thick. It rests on a metal plate connected to earth and another metal plate c fits into the recess. To make contact between this plate c and the needle a small glass vessel containing sulphuric acid, into which dips the rod of the needle, rests on this plate and a wire d makes contact between the acid and plate. If the surface of the ebonite deteriorates it may easily be cleaned by removing the surface by fine emery paper or by scraping.

The sulphuric acid in any of these forms of condenser often presents a troublesome difficulty. After standing for a considerable time a film forms on the surface and the surface tension between this film and the rod of the needle affects the motion of the needle in a troublesome manner. This may be overcome by stirring the acid thoroughly or by renewing it. As the acid absorbs moisture rapidly care must be taken that it does not overflow the vessel and ruin the instrument.

To secure sensitiveness in the instrument the needle should be made as light as possible consistent with rigidity. It may be made of thin aluminium just thick enough to maintain its shape rigidly or it may be made of paper silvered on the surface to make it conducting. Many of even the older types of instrument may be made quite sensitive by fitting them with a light needle. The needle should be perfectly symmetrical in shape.

The suspension for the needle should be very light if great sensitiveness is required. The most satisfactory non-conducting suspensions are fine quartz fibres. These can either be made in the laboratory or may be obtained from instrument makers

in different grades of thickness. The fibre may be attached at the ends to the metal parts of the instrument by a minute portion of hard wax. Care must be observed that the wax used is of a comparatively rigid nature so as to prevent any movement at the joint when the suspension is under torsion.

To communicate the charge to the insulated needle it is convenient to use a wire W (Fig. 7), passing through an ebonite plug in the top of the instrument and bent twice at right angles, so that the lower arm may be turned round in contact with the stem of the needle. The upper arm can then be placed in contact with a set of small accumulators or other source of potential.

To maintain the potential of the needle constant we would strongly recommend using a conducting suspension instead of the insulating quartz by means of which the needle can be kept permanently connected to a set of small accumulators or other cells: A very light phosphor-bronze galvanometer suspension will be found very satisfactory. The potential of the needle may thus be kept perfectly constant and may be altered by any definite amount at will and the sensitiveness may be maintained the same day after day. Using this method the condenser may be discarded and all the accompanying difficulties of insulation, etc., eliminated.

The mathematical theory of the electrometer generally found in text-books is somewhat faulty. The result is usually given about as follows: If V_1, V_2 and V_3 are the potentials of the two pairs of quadrants and the needle respectively, and F is the torsional couple for a deflection of unit angle, then for a deflection θ the relation given is

$$F\theta = a(V_2 - V_1)[V_3 - \tfrac{1}{2}(V_1 + V_2)],$$

where a is a constant. It follows from this that if V_3 be very large compared with both V_1 and V_2 then $\tfrac{1}{2}(V_1 + V_2)$ may be neglected and

$$F\theta = a(V_1 - V_2)V_3,$$

and therefore for a given difference of potential between the quadrants the deflection θ will be proportional to the potential of the needle. It is found however by observation that in most electrometers the deflection at first increases with increase of potential on the needle until it reaches a maximum and then decreases with further increase of potential. Recently G. W. Walker has developed a theory in which he accounts for this maximum value for θ followed by a decrease by the presence of the air-gap between the quadrants which causes the capacity of the needle to alter as it moves past this air-gap. He obtains a modified equation, namely,

$$(F + 2bV_3{}^2)\theta = a(V_2 - V_1)V_3,$$
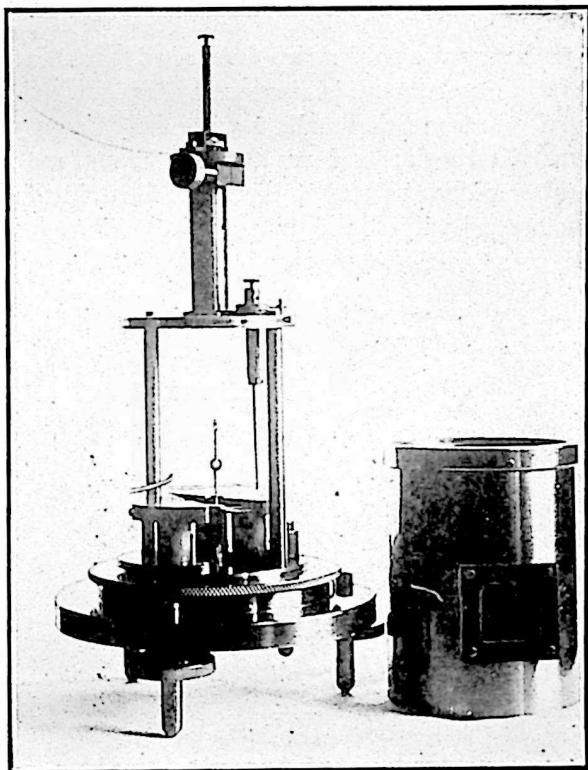
Fig. 8.

where b is a constant, and assuming as before that V_3 is large compared with V_1 and V_2 which is a fact in the ordinary method of using the instrument. From either theory it follows though, that for a given potential of the needle, the deflection is proportional to the difference of potential between the two pairs of quadrants. In most cases in actual practice this is the important condition as a basis of measurement.

11. **Dolazalek Type of Electrometer.**—The type of electrometer devised a few years ago by Dolazalek is, in the opinion of the author, the most useful and satisfactory instrument of its kind made at the present time for the class of work with which we have to deal, and if an electrometer is to be acquired for a laboratory this type is most strongly recommended. The advantages of this instrument over older forms consist chiefly in the simplicity of construction and consequent elimination of troublesome factors and in the increased sensitiveness. A diagram of the instrument is shown in Fig. 8.

The set of quadrants is small, usually only from 5 to 6 cm. in diameter. In the latest form the quadrants are supported on stout amber pillars as amber is an excellent insulator. The needle is extremely light and is made of silvered paper and consists of two layers of paper fastened at the outer edges
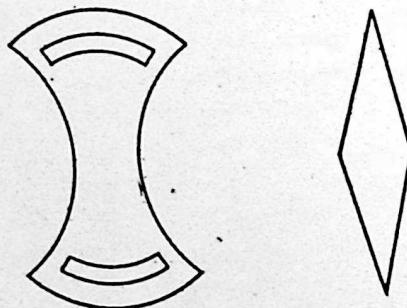
FIG. 9.

and spread apart at the center to secure rigidity. Broadside and edge-on views of it are shown in Fig. 9. Being so extremely light and lying very close to the quadrants the needle is suffi-

ciently damped by the air and requires no other damping. The conducting phosphor-bronze method of suspension with permanent connection to the battery is the most satisfactory to use. Usually a potential of from 80 to 100 volts on the needle will be found convenient.

With a fine quartz suspension the instrument may be made very sensitive, as much as 10,000 dimensions per volt on a scale about 1.5 meters distant having been obtained. It is however not at all advisable to work with the instrument under such sensitive conditions, for the needle is very unstable and will not maintain a steady zero position and is very easily disturbed by the slightest outside influence. For most work a sensitiveness of anywhere from four to six hundred divisions per volt on a scale about 2 meters distant will be found suitable. The sensitiveness depends upon the thickness of the suspension and the charge on the needle.

The whole instrument is enclosed by a tightly fitting brass case with a window through which to observe the mirror on the needle.

12. Adjustment of Lamp and Scale.—The stem of the needle should be fitted with a small and very light concave mirror, preferably not more than 6 or 7 mm. in diameter, having a focal length of about 50 cm. Obtain the image of an incandescent electric lamp filament on a scale at a distance of 1.5 or 2 meters away from the mirror. Adjust the position of the lamp so that a sharply defined image of the lamp filament is obtained in a vertical position on the scale. Place the lamp a little below the level of the mirror so that the reflected beam of light may pass directly over the top of the lamp, causing the plane of the incident and reflected rays to be vertical. Place the scale at right angles to the beam of light by carefully measuring equal distances from the mirror to the ends of the scale when the image is at the centre of the scale. A white millimeter paper scale about a meter long fastened to a board which may slide horizontally in grooves so as to be adjustable to any zero point will be found convenient. As the image of the lamp filament may have a considerable width, select one edge of the image and use it as the line to read by on the scale.

13. Adjustment of Electrometer.—Set the electrometer up in a dry atmosphere on a firm support such as a slate slab resting on a stone or brick pillar, so that there may be no vibration. Carefully level.the instrument so that the quadrants are level. Adjust the position of the needle until it hangs symmetrically with regard to the quadrants, that is, so that the line bisecting the needle lengthwise is parallel to the air line bisecting the circle of the quadrants. After this is adjusted as nearly as possible by the eye test the symmetry by charging the needle, having all the quadrants connected to earth. If everything is symmetrically situated the zero of the needle should not alter. If the needle does not remain at zero when thus charged adjust it by trial till it does. In some instruments one of the quadrants is also adjustable in position. A further test of the symmetry should be made as follows: One pair of quadrants being to earth, charge the other pair to a given positive potential and observe the deflection, then change the potential to an equal negative one and observe the deflection on the opposite side of the zero. These two deflections should be exactly equal if everything is symmetrical.

In all instruments the quadrants are always connected in pairs and each pair connected by insulated wires to two insulated terminals on the outside of the instrument. The insulation of the quadrants and terminals should be perfect, as defective insulation is fatal to accurate measurements. Test the insulation as follows: One pair of quadrants being connected to earth, disconnect the other pair from everything else and charge them up by connecting them for an instant to one pole of a battery, the other pole being to earth. Use a small potential for this; only a fraction of a volt will be sufficient. Having removed the charging wire observe the reading of the needle when it comes to rest. If the insulation is perfect this reading should remain steady, but if the insulation is defective the needle will gradually return to zero, showing that the charge is leaking off the quadrants. The insulation should then be removed and cleaned unless the leakage is so small that it will not affect appreciably the measurements to be made.

The air inside the instrument ought to be thoroughly dry. If the instrument is one in which no condenser with sulphuric acid is used a small quantity of drying material may be introduced in a convenient place with advantage.

14. Screening.—There are usually stray electrostatic charges produced by friction or other causes in the neighborhood of the apparatus in use, especially in a dry atmosphere. These charges are sure to cause serious electrostatic disturbances either by direct contact with the electrometer and connections or by induction. Even the movement of one's body near the electrometer will often cause violent disturbances of the needle. It is therefore absolutely essential to enclose the electrometer and all insulated parts of the apparatus and wire connections within metal screens connected to earth so that any outside disturbance may not reach the insulated parts of the apparatus. All parts which are not required to be insulated must be connected to earth. A convenient way to do this in most laboratories is to solder a fairly heavy bare copper wire permanently to a water pipe or gas main which runs into the earth and all earth connections may be made to this wire. It is not sufficient to merely wrap this wire around the water pipe; good solder connection must be made. If this earth connection of the different parts be neglected these parts become charged up and cause disturbances which are usually indicated by the erratic action of the electrometer needle.

In setting up an electrometer for permanent use the following method of screening will be found most convenient: Place a large sheet of metal about three feet square on the table and set the electrometer on this. Make a rectangular cage of wire gauze about three feet each way enclosed on all sides but the bottom. This may be set over the electrometer on the metal sheet. One whole side of this cage should be made removable either in the form of a door or otherwise. The cage and door are made large so that the electrometer may be conveniently reached to make adjustments, and in addition several other pieces of small apparatus such as connecting keys, etc., may be placed inside the screen, thus saving additional screens. Con-

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nect the whole cage permanently to earth. Connections from outside and the light falling on the mirror of the needle may be admitted into this screen through small holes cut in the gauze.

The following method of screening insulated wires connecting separate pieces of apparatus has been found very convenient: Take a brass tube of the required length about 2.5 cm. in diameter and across each end fix a piece of clean stick sealing wax as shown in Fig. 10. This may be done by heating the end of the tube slightly and pressing the sealing wax on to it. The wire to be screened is run through the tube and one end fastened to the sealing wax by slightly heating the wire and pressing it into the wax. When this hardens the wire may be drawn tightly at the other end and fastened in a similar way. The wire remains tightly stretched along the axis of the tube. The wire used should be of small diameter so as to be flexible
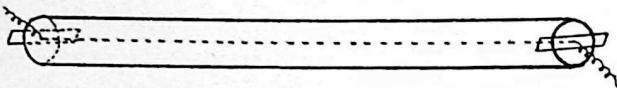
FIG. 10.

and easily stretched. For this purpose a fresh stick of sealing wax should be used and the insulating surface must not be handled by the fingers or destruction of the insulating quality is likely to result.

15. Insulation.—The question of insulation in electrostatic work is quite a different problem from what it is in ordinary current work, for what in ordinary current work would be perfect insulation is useless as such in electrostatics. Since the electrostatic charges to be measured are usually small a small leakage will cause quite a serious error. The different so-called insulators differ somewhat in quality for electrostatic uses. Amber and ebonite are good permanent insulators and possess the advantage of being workable into any shape in a lathe. A particular quality of artificial amber supplied by instrument makers is excellent. Sulphur is a most excellent insulator for this work, but has the disadvantage of being brittle and is apt to crack after being cast in

large pieces. For small insulators it is excellent. In making up small sulphur beads use a clean piece of stick sulphur and melt it very carefully in a clean porcelain dish, and just when it reaches a clear liquid state use it for moulding whatever is required. If it is heated beyond this stage it loses its insulating quality. Sealing wax is very excellent where no strain is to be put upon it. If it is heated in adjusting it in position care must be taken not to char it as it will lose its insulating quality if burned. Paraffin is a fair insulator when pure but has the serious disadvantage of retaining very persistently any charge on its surface as the charge seems to penetrate below the surface and is removed with difficulty. Glass is not of much value in this class of work as an insulator unless coated with some other insulator, such as paraffin or sulphur.

The first general precaution in this regard is that the surface of the insulation must be perfectly clean. The outer film of the surface should be entirely removed by scraping or otherwise, so as to leave a fresh surface. After the surface has been cleaned it should not be touched with the fingers, for the slightest contamination destroys the insulating properties. This precaution is often neglected and trouble ensues. Moisture and dust even in small quantities on the surface of insulation should be guarded against. The atmosphere of the room where work is done should therefore be kept dry. It will be necessary in many instances to dry the air in and around the apparatus by means of chemical drying materials.

Troublesome disturbances often arise from the surface of the insulation acquiring an electrostatic charge. This is usually manifest by the erratic action of the electrometer needle when the quadrants are insulated. This surface charge can usually be removed by passing a Bunsen flame quickly over the surface. Another method of removal is to place a small open vessel of uranium oxide close to the charged surface, when the ionization produced by the uranium will allow the charge to leak away through the air.

In a complicated system of insulators it is sometimes rather difficult to locate the exact position of the leak due to a de-

fective insulator. To do so insulate the whole system and charge it up and observe the deflection of the needle as explained in § 13 in connection with the test of the insulation of the quadrants. Then cut off the conductor in the system farthest from the electrometer and test again. If the leak does not appear now it must have been in the insulation of this conductor. If it does appear cut off the next farthest conductor and test and continue this one by one until the leak is located. Then clean or replace the insulation.

Flames of any kind should not be allowed in the neighborhood of any object which requires to be insulated, as the ionization produced by flames in the air destroys the insulating property of the air. Any radio-active substance in the vicinity will cause the same difficulty.

16. Electrometer Keys.—As any movement of the observer near the electrometer connections is apt to cause electrostatic

FIG. 11.
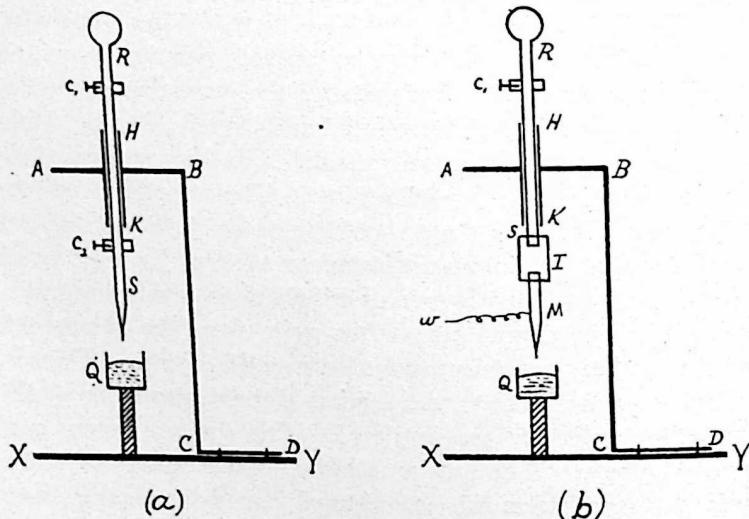
disturbances and as all the connections must be carefully enclosed in earth-connected screens, it is both expedient and convenient to place all connecting and disconnecting keys inside

the cage with the electrometer and work them from a distance. The keys shown in Fig. 11 are most convenient forms.

The key shown at (*a*) is used for alternately connecting to earth and insulating one pair of quadrants of the electrometer and connections. A piece of sheet brass one sixteenth inch thick and an inch wide and nine inches long is bent twice at right angles, making the upper part *AB* two inches in length and *CD* one and a half inches. A brass tube *HK* about $\frac{1}{8}$ inch inside diameter and 2.5 inches long is fitted and soldered at right angles to *AB* through a hole near *A*, so that it projects $\frac{3}{4}$ inch below *AB*. A brass rod *RS* about six inches long and pointed at *S* slides loosely through *HK* and has two small adjustable clamps C_1 and C_2, so that it moves within defined limits. This rod may be drawn up by a cord attached to the ring at the top and allowed to fall under its own weight. This system is fastened to a piece of heavy sheer metal *XY* and the whole thing connected to earth. An insulated metal mercury cup *Q* is placed so that *S*, when lowered, will dip into it. The electrometer quadrants and connections are connected with the mercury cup, and when the rod *RS* dips into *Q* they are all connected to earth through *ABC* and when *RS* is raised they are insulated.

One precaution must be carefully observed here which applies to all cases where electric contact is made between mercury and other metals, such as brass and copper. The surface of the metal in contact with the mercury must always be amalgamated, by dipping first in nitric acid and then rubbing mercury over the surface, so as to eliminate contact difference of potential effects at the juncture of two dissimilar metals. The end of the rod *S* and the inside of the cup *Q* must be amalgamated. Otherwise the electrometer needle will be deflected when the contact is broken, due simply to the change of potential at the separation of the two dissimilar metals brass and mercury.

After experimenting for some time with different forms of mercury cups and other contacts for *S* the author found the form of cup and insulator shown in the diagram the most

satisfactory. Q is a small brass cup about 1 cm. inside diameter and 1 cm. deep and it rests on a stick of clean sealing wax about 3 cm. high. The sealing wax is fastened to the cup above and the plate below by slightly heating the metals and sticking the wax to the warm metal.

Mercury cups have often been made by boring a hole in a block of paraffin and filling with mercury, but they are not satisfactory as the paraffin becomes charged up on the surface by the friction of the key and mercury and otherwise, and this charge does not disappear immediately when the cup is earthed on account of the retentive quality of the paraffin. In all cases of this sort the area of the insulating surface should be reduced as much as possible.

A slight modification (b) of the above form of key has been found very convenient for making contact between two insulated connections within the electrometer screen, such as for instance connecting a standard cell to the electrometer or connecting a separate charged condenser with the electrometer. The rod RS, instead of dipping into the mercury cup, is fitted tightly into a rod of ebonite I about an inch or so long and into the other end of the ebonite is fitted another brass rod M which may dip into the mercury cup. M is thus insulated from earth by I and is connected to the cell or other object by a thin flexible wire w. The rest of the key is identical with (a).

These keys are raised by means of a cord which runs over a pulley in the ceiling vertically above the key and is thence carried to any desired position by another pulley placed about vertically above the scale where the observer is situated when taking readings.

17. Standardization of Electrometer.—To convert the scale readings into definite electrical units these readings must be standardized by observing the deflections produced when a known potential is applied to the quadrants. If the electrometer is not too sensitive one pole of a standard Clark cell or Weston cell may be applied directly to the insulated pair of quadrants by means of the key (b), Fig. 11, while the other pole is connected to earth. To guard against accidentally

short-circuiting the standard cell by neglecting to insulate the quadrants from earth before connecting the cell to them a large resistance of about 10,000 ohms should be placed in series between the one pole and the earth, so that in case of accident the cell would not be injured. If the deflection produced by the cell is not too great for the length of scale used observe the deflection produced by the known voltage of the cell. If the deflection is too great for the length of scale connect the cell through a potentiometer of large resistance and tap off from the potentiometer a known potential sufficient to give a suitable deflection. Since the deflections are proportional to the difference of potential between the quadrants the number of scale divisions per volt is known. This value is technically termed the sensitiveness of the instrument. Any other deflection on the scale can therefore be converted into volts by direct proportion. The sensitiveness of course depends upon the potential of the needle and the instrument must consequently be standardized each time observations are made if there is any change of potential of the needle.

18. **Connection of Electrometer to Other Apparatus.**—The wires connecting the electrometer to any other apparatus, on which experiments are being conducted, must be screened in metal tubes connected to earth as already described, § 14. The typical general arrangement of electrometer, lamp and scale, key, screen, etc., is shown in the diagram, Fig. 12, which is
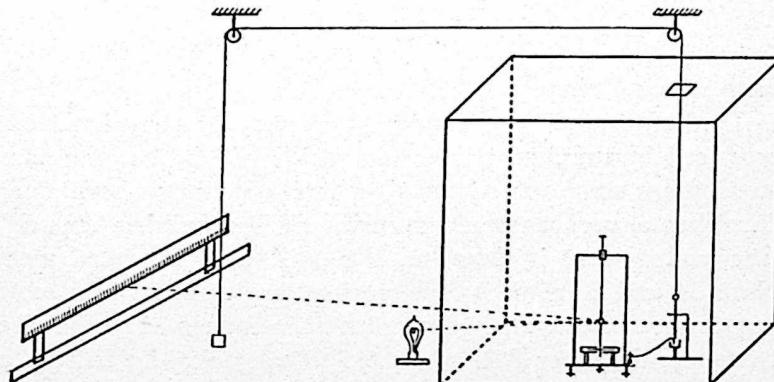
FIG. 12.

self explanatory. The apparatus to be tested would be connected, by a screened wire passing through the cage, to the mercury cup in the key. The metal tube screening this connecting wire should pass inside the main cage so that no part of the wire is exposed.

19. Determination of Capacity of Electrometer and System. —In making definite calculations from the observations with the electrometer it is often necessary to know the capacity of the electrometer and connections. One method of determining this is by the ordinary method of mixtures.

Let $C =$ the capacity of electrometer and system connected with it,

$C_1 =$ the capacity of a known standard condenser.

Charge up the electrometer and connections by means of a battery to a potential V and let the deflection of the needle be d divisions on the scale. Then connect by means of a key (b), Fig. 11, the standard condenser in parallel with the charged electrometer, etc. The charge will then be divided between the electrometer system and the standard condenser. Let the resulting potential $= V_1$ and the corresponding scale reading $= d_1$; therefore $CV = (C + C_1)V_1$, since the total charge is constant.

Therefore
$$\frac{C}{C + C_1} = \frac{V_1}{V} = \frac{d_1}{d},$$

or
$$C = \frac{d_1}{d - d_1} \cdot C_1,$$

from which C may be calculated.

Another method depending upon the very constant ionization produced by uranium oxide, and which will be better understood after some experiments on ionization have been done, furnishes a very convenient means of determining capacity. The arrangement is shown in Fig. 13. Two insulated metal plates A and B, about 15 cm. square, are enclosed in a metal box connected to earth. One plate A is connected to the electrometer; the other B is connected to one pole of a battery of accumulators of about 200 volts, the other pole being to earth.

On B is sprinkled a small quantity of uranium oxide which produces a constant amount of ionization in the gas between A and B. For a given constant source of ionization and a given potential on B the rate at which A charges up is proportional to the capacity of the system. Let C be the capacity of the electrometer, ionization vessel and connections and let d be the number of scale divisions passed over per second as
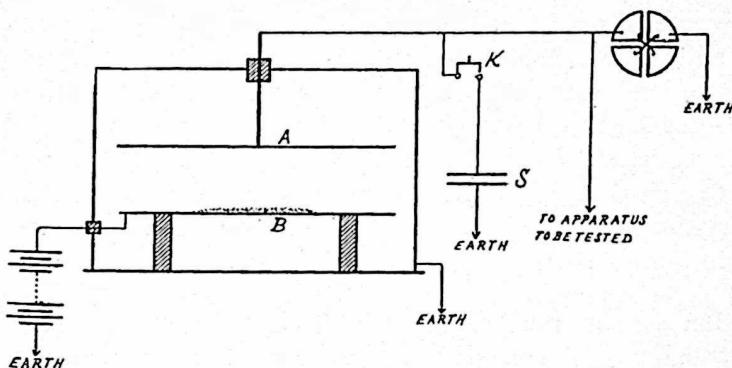
FIG. 13.

A charges up, and let the potential acquired by A per second be V. Now connect a standard condenser S of capacity C_1 in parallel by means of the key K and let the number of scale divisions per second be d_1 and the potential acquired per second be V_1. Then, since the charge acquired in each case is the same,

$$CV = (C + C_1)V_1.$$

Therefore
$$\frac{C}{C + C_1} = \frac{V_1}{V} = \frac{d_1}{d};$$

or
$$C = \frac{d_1}{d - d_1} C_1;$$

from which C may be calculated as before.

This method has the advantage of convenience and even reliability, and in addition has the advantage of the capacity

being determined with the needle in motion under conditions similar to those under which the actual test measurements are made. It has the slight disadvantage however that the capacity determined includes the capacity of the ionization vessel, which cannot be eliminated and therefore it must be kept constantly connected to the electrometer during all the experimental measurements. The uranium oxide however must then be removed and everything connected to earth except the plate A.

20. Typical Measurement of Current by Electrometer.— As a guide to the method of measurement and calculation of a current by the electrometer a typical example will be given. The usual method of measurement is to observe the time rate at which the electrometer quadrants charge up, that is, the quantity of electricity transferred through a gas per second to a conductor connected with the electrometer.

Let q = the number of coulombs of electricity received by the electrometer quadrants and connected system per second.

Let the capacity of the whole system in microfarads (in which units condensers are usually made) be C, which will equal $C/10^6$ farads.

Let V = the rise of potential of the system per second in volts.

Therefore
$$q = \frac{C}{10^6} \times V.$$

Therefore since the current equals the number of coulombs per second, the current i will equal $CV/10^6$ amperes.

The deflection of the electrometer needle is proportional to the difference of potential between the two pairs of quadrants.

Let d = the number of scale divisions moved over per second as the quadrants acquire their potential V.

Let d_1 = the number of scale divisions corresponding to a difference of potential of 1 volt as determined from a standard cell.

Therefore $$V = \frac{d}{d_1};$$

or $$i = \frac{C}{10^6} \times \frac{d}{d_1} \text{ amperes.}$$

In practice the capacity of a Dolazalek electrometer system without any extra condenser is usually about 50 electrostatic units, which we will take as a typical case.

Therefore $$C \text{ will } = \frac{50}{9 \times 10^5} \text{ microfarads,}$$

since 1 microfarad $= 9 \times 10^5$ electrostatic units. Suppose that $d_1 = 600$ divisions and $d = 10$ divisions per sec.; then will

$$i = \frac{50}{9 \times 10^6} \times \frac{1}{10^6} \times \frac{10}{600}$$

$$= 9.2 \times 10^{-13} \text{ amperes.}$$

21. Preliminary Experiments with the Electrometer.— Before attempting any definite ionization measurements with the electrometer one should become perfectly familiar with the instrument by a little preliminary manipulation. (1) In the first place the electrometer, its lamp and scale, keys and all accessories should be very carefully set up and adjusted as already explained. It pays to spend a little time on the preliminary setting up as subsequent experiments will be performed with much greater ease and accuracy. (2) Test the sensitiveness of the instrument for various potentials on the needle. (3) Connect a storage battery of a couple of volts across a potentiometer and measure in volts by the electrometer the potential across different portions of the potentiometer.

22. Electroscopes.—The gold leaf electroscope was one of the earliest electrical instruments. In its older forms it was used chiefly as a detector of the presence of an electric charge and was not well suited to accurate quantitative measurements.

Since there has arisen of late years the need of a delicate and accurate instrument to measure currents too small to be measured even by an electrometer the electroscope has reached a high state of perfection. It assumes somewhat different forms when applied to certain special cases, but the form shown in Fig. 14 is the general type of instrument used and will serve for most purposes where an electroscope is required. AB is a metal case which may vary in size according to the purpose for which it is required, but a convenient size is one of about a liter capacity. C is a tightly fitting ebonite plug about 2.5 cm. diameter. A metal rod D about 1 mm. diameter, passes through the ebonite, and on the end of it is a piece of amber or a bead of sulphur to insulate the gold leaf system.
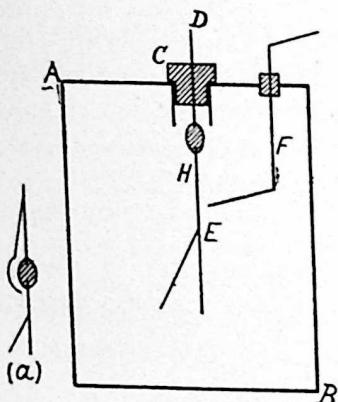
FIG. 14.

In making this sulphur bead great care must be taken to secure good insulation. It may be made as follows: Heat very gently a small quantity of clean stick sulphur in a clean porcelain evaporating dish until it melts. When it becomes a clear liquid dip the end of the rod D into it and, withdrawing the rod, allow the sulphur to harden. Repeat this continuously until quite a large bead has accumulated on the end of D. Great care must be taken in heating the sulphur to prevent heating it too much and it must only be used just at the clear liquid stage, for if it is heated too much and goes beyond this stage its insulating property deteriorates very much, and it becomes almost useless as a perfect insulator. Take another flat metal rod H from 5 to 7 cm. long and form another sulphur bead on the end of it; then dip both these beads into the liquid at once and stick them together so the rods are in a straight line and let them harden. If desired the surface of

the sulphur may be trimmed off with a sharp knife, but carefully avoid touching the surface with the fingers and keep the surface clean.

At E a narrow strip of gold or aluminium leaf from 3 to 4 cm. long and 1 to 2 mm. wide is attached by a touch of gum. The leaf should be cut between two sheets of paper and with as smooth an edge as possible so as to give a sharp line in the reading microscope. For very sensitive electroscopes the leaf should be cut as narrow as possible. This may be done by pressing the edge of a sharp razor full length flat against the leaf between the paper and carefully sawing the razor back and forth. By this means strips a small fraction of a millimeter in width can be cut.

To charge the gold leaf system a wire F passing through an ebonite plug and bent twice at right angles may be used. This can be turned round so that one end touches H above the gold leaf and the charge may be communicated from a battery. F must then be turned away and connected to earth. If the case AB is required to be air-tight for any reason F may be replaced by a flexible piece of steel spring wire attached to the rod D as shown in (a) Fig. 14. This wire may be drawn into temporary contact with H by a magnet from outside.

After the gold leaf system is charged and when readings are being made every part of the instrument but the gold leaf system must be carefully connected to earth, for if any part of the instrument is insulated and becomes charged in any way the gold leaf will be disturbed, as it is so sensitive. For this reason glass or any other insulating material should never be used as a case for the electroscope unless it is coated on the inside by some conducting material such as tin foil or a silver coating from a silvering solution or something of that nature. Non-conducting material as a case for an electroscope is to be avoided wherever possible. Neglect of this precaution is often the cause of serious disturbing influences and erratic movements of the gold leaf. For this reason also the necessary insulating parts should be made as small as possible consistent with good insulation, so that there may be as small a surface as possible to become charged up.

23. Illumination of Gold Leaf and Scale.—Two small windows should be made in the front and back of the case opposite each other and in line with the leaf. The openings may be closed by thin sheets of mica waxed down around the edges. An incandescent lamp or other steady illumination should be placed a little distance, a foot or more, behind the back window so as to illuminate the field. Care must be exercised with regard to this illumination as the heat from it sometimes produces air currents in the electroscope and causes erratic movements of the gold leaf, especially just after the illumination is turned on. Where observations extend over several hours even at intervals it is best to keep the illumination turned on all the time and to allow a little time to elapse at the beginning after turning on the light before taking readings to allow the conditions to become steady.

24. Adjustment of Reading Microscope.—The movements of the gold leaf are viewed through a reading microscope with a micrometer scale within it. The usual method of using the electroscope is to charge up the leaf system and then observe the rate at which this charge leaks away through the surrounding gas due to ionization in the gas from any cause. This rate of leak is observed by noting the time it takes the gold leaf to pass over a given number of scale divisions as it gradually falls due to loss of charge. The time is taken by means of a stop watch.

Set up the microscope in front of the window of the electroscope and carefully focus it on the leaf so that a clear image of the leaf is seen on the micrometer scale. As the edge of the leaf usually appears somewhat ragged in the microscope due to magnification select a definite point on the leaf to observe and adjust the microscope so that this point is on the scale. As any given point on the leaf in falling is really moving in a circle round E (Fig. 14) as centre and not in a horizontal line the micrometer scale should be tilted at an angle to the horizontal so that the leaf in losing its charge will move over as nearly as possible equal lengths of scale for equal losses of charge. Even with this adjustment the leaf will not

move over the whole range of its motion at the same rate and therefore when different readings are being compared the readings should all be made over the same portion of the scale, that is, the time taken for the leaf to pass over the distance between the same two fixed points on the scale should be observed in each case. This precaution is essential, for if the readings are taken over different sections of the scale discordant figures are likely to result.

25. Calibration of Electroscope.—To make absolute determinations of current by the electroscope the scale divisions must be standardized in terms of volts. To do this connect a battery of known voltage, say three or four hundred volts, to a potentiometer of large resistance from which definite known potentials may be tapped off. Charge the gold leaf to sufficient potential to deflect it to a point near the beginning of the portion of the scale over which readings are to be taken and note the reading; then increase the potential by a known amount so as to increase the reading to about the upper limit of the region over which readings are to be taken. Note this reading and the difference in the two readings will therefore correspond to the known increase of voltage. Several voltages between these two extreme ones should also be taken and the readings noted to test whether the readings over the different parts of the scale used are proportional to the voltage. If they are not a careful calibration over the part of the scale to be used should be made and a calibration curve plotted. Any movement of the leaf across the scale will then correspond to a known change of potential of so many volts.

26. Capacity.—The capacity of an electroscope is sometimes required in making absolute quantitative measurements. This may be determined by the method of mixtures already described, § 19, in connection with the electrometer.

27. Typical Measurement of Current by the Electroscope.—A sample measurement of a very small current by an electroscope will be given as illustration. If C is the capacity of the electroscope in farads and V the loss of potential in volts per second then as in the case of the electrometer $i = CV$.

In practice the capacity of a gold leaf system of an average sized electroscope of about 1,000 c.c. in volume is usually about one electrostatic unit. Suppose the loss of potential were 10 volts per hour, which could easily be measured, then the loss per sec. would be 10/3600. Therefore the current through the gas would be

$$i = \frac{1}{9 \times 10^{11}} \times \frac{10}{3600} \text{ ampere,}$$

since 9×10^{11} electrostatic units $= 1$ farad.

Therefore $i = 3.08 \times 10^{-15}$ ampere.

An even smaller rate of leak of the gold leaf system may easily be read with accuracy so that the electroscope is capable of measuring much smaller currents than in the electrometer.

28. Preliminary Experiments with the Electroscope.—A few preliminary experiments should be performed with the electroscope to familiarize oneself with its use.

1. Carefully set up an electroscope with its reading microscope and accessories and adjust them carefully as already described.

2. Calibrate the scale carefully over its whole workable range and plot a calibration curve with volts for ordinates and scale divisions for abscissæ.

3. Measure several known voltages across a potentiometer.

4. There is always a certain amount of natural electrical conductivity through the air which is usually termed the natural leak of the electroscope (see Chapter XVI). Measure this carefully and calculate the current through the air in amperes.

Note.—In using the electroscope to measure ionization currents this natural leak of the instrument is always present and must be corrected for as it is included in the total rate of leak measured. It must therefore always be measured as a preliminary experiment and subtracted from the total rate of leak to obtain the true current whose value is required.

29. Condensers.—Another class of instrument of very frequent application in this line of work is the condenser. In many cases the rate at which the electrometer charges up is far too rapid to be read with any degree of accuracy or even at all. This rapid rate has to be cut down to readable dimensions by adding capacity in parallel with the electrometer. An adjustable condenser of known capacities is therefore necessary. If one or more standard subdivided condensers are available the problem is solved, but as they are expensive they are not available in most laboratories for more than a very few students.

(*a*) *Standard Condenser.*—A simple form of condenser which may be used as an absolute standard may be easily made in the form shown in Fig. 15. Two brass tubes of equal
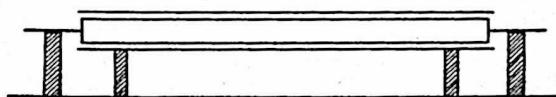
length, each of uniform size throughout and one a little smaller than the other, are placed with their axes coincident. The inner one is supported and insulated by two ebonite supports, while the outer one does not necessarily require to be insulated. If this is made accurately its capacity C in electrostatic units may be calculated by the ordinary formula

$$C = \frac{l}{2 \log_e \frac{b}{a}},$$

where l is the length of each of the cylinders, a the external diameter of the inner cylinder and b the internal diameter of the outer one.

(*b*) *Sulphur Condenser.*—A working condenser of small capacity may be made as follows: Make 20 or 25 plates of brass or zinc, all of the same size and each about 100 square cm. area

and about o.5 mm. in thickness. Fasten half of the number
rigidly by one edge to a brass rod at right angles to their planes
so that they are all exactly parallel to each other and about o.5
cm. apart. Do the same with the other half and then place the
plates of one set within the spaces of the other set so that they
are equally spaced and parallel. Fasten these two sets rigidly
by clamps in this position, being careful that they are ac-
curately spaced and place them inside a vessel to act as a
mould and fill the mould with pure sulphur melted to a clear
liquid. When it hardens remove the mould. The capacity
of this condenser will of course have to be measured by com-
parison with the standard condenser, using the electrometer in
one of the methods already described. Condensers of a variety
of sizes may be made after this pattern.

(c) *Paraffined Paper and Tinfoil Condenser.*—A condenser
of fairly large capacity in small compass may be simply made
with sheets of tinfoil and paraffined paper. Dip sheets of
thin paper of say a foot square or more in melted paraffin so
they are thoroughly saturated and then allow to dry. Build
up a condenser with these paraffined paper sheets as dielectric
between alternate sheets of thin tinfoil. The dimensions of
the tinfoil sheets should be from 1.5 to 2 inches smaller each
way than the paper so as to ensure good insulation at the edges.
Each tinfoil sheet may be made with a tongue projecting. from
one edge to which connection may be made. The alternate
sheets should be placed so that the projecting tongues are
situated at opposite edges, so the sheets of each set or any
portion of them may be easily ·connected together. A con-
denser of quite a large capacity may be made in this form,
and besides being comparatively cheap and easily made it has
the advantage that any ·portion of the total number of plates
may be used at a time by disconnecting the remainder and con-
necting them to earth. The capacity may be calculated ap-
proximately by the ordinary formula for a plate condenser or
it may be measured directly by comparison with a standard.

(d) *Adjustable Condenser.*—If the actual capacity of the
condenser is not required to be known and if small variations

and fine adjustments of capacity are required for any purpose a convenient form of sliding condenser may be used. A set of parallel metal plates 20 or 25 cm. square and all fastened rigidly together at the bottom about a centimeter apart are placed in a vertical position. Another similar set is hung from two horizontal well-insulated rods parallel to the plane of the first set on which the second set of plates may slide between those of the first set. By sliding the upper insulated set of plates between those of the other set the capacity may be increased and quite fine adjustments made.

30. Production of High Vacua.—As a great many experiments in this work have to do with low pressures a few details will be given in this regard. There are a variety of vacuum pumps which may be used. When rapid exhaustion is required a Fleuss pump is very suitable if a pressure not lower than about a millimeter is desired. If a pressure not lower than the aqueous vapor pressure is required the ordinary vacuum pump attached to the water tap is very convenient for rapid work. But in the opinion of the author the most satisfactory pump for general use, especially in the exhaustion of glass discharge vessels of all kinds, such as cathode and X ray tubes, is the glass Toepler mercury pump as described in general text-books of physics.

The form generally given in text-books is shown in (*a*) Fig. 16, but a great improvement on this is shown in (*b*) at the point A, where the side-tube T joins on above the reservoir R. When in use the reservoir S is first raised and then lowered; the difference in pressure between the vessel which is being exhausted and the reservoir R forces the air from this vessel through the mercury in T and, unless extreme care is taken at the first stages of exhaustion, it drives the mercury with considerable force at right angles to the tube at A and is very liable to break the glass at a very critical joint. In the form in (*b*), however, the mercury does not strike the tube at right angles but comes round the curve and shoots into the reservoir R, and the danger of breakage is very greatly lessened. A very high vacuum may be obtained with this pump.

There is one slight drawback with this pump, namely, the presence of mercury vapor at low pressures. This may however be very easily remedied by placing a quantity of gold leaf loosely rolled up in the tube connecting the pump with the vessel to be exhausted. The gold leaf absorbs the mercury vapor before it reaches the vessel, which may thus be kept quite free from vapor.

For measuring the gas pressures down to about a millimeter or two a good manometer should be available along with a

(a)   (b)
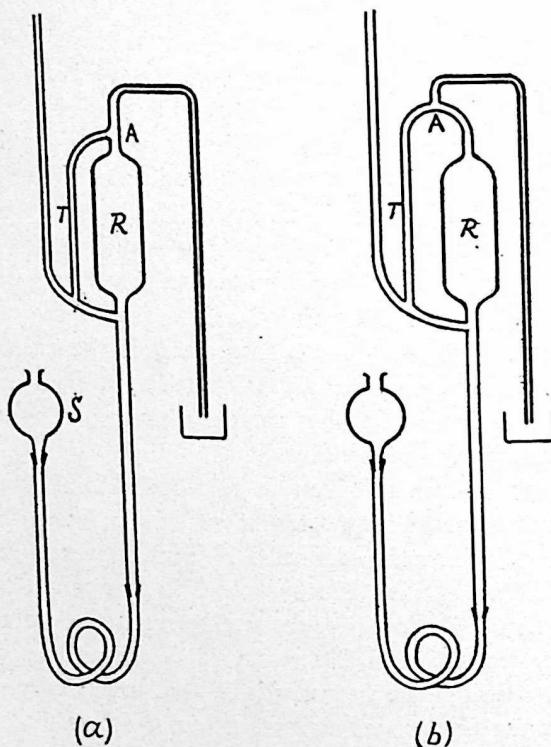
FIG. 16.

good barometer. For lower pressures a McLeod gauge may be used.

- A comparatively rapid and simple method of obtaining a low pressure depends upon the property possessed by charcoal

made from cocoanut, by virtue of which it will, at the temperature of liquid air, absorb many times its own volume of air and other gases. If a quantity of this charcoal be placed in a glass side tube connected with the vessel to be exhausted and this tube be immersed in liquid air the air in the vessel will be rapidly absorbed and in a few minutes a pressure low enough for the production of cathode rays may be obtained even without any previous exhaustion. The quantity of charcoal necessary will of course depend upon the volume of gas to be absorbed. This is an excellent method of securing a very high vacuum by first pumping most of the air out and then causing the charcoal to absorb the remainder. In order to maintain the high vacuum the charcoal must of course be kept in the liquid air, as when its temperature is allowed to rise it allows the absorbed air to escape again into the vessel.

A troublesome difficulty arises in the removal of the air from such vessels as cathode ray and Röntgen ray tubes from the fact that after the low pressure has been obtained the pressure slowly rises slightly again, due to the air occluded by the walls and other parts of the vessel gradually escaping into the vessel under the diminished pressure. This is noticeable if the vessel be allowed to stand a while after being exhausted, or if the walls of the vessel be slightly heated, or again in the case of an electric discharge tube of any kind if the discharge be caused to pass. The heating of the vessel or the passage of the discharge causes the occluded air to escape from the walls or electrodes of the vessel. In making a permanent Röntgen ray tube or anything of that nature the vessel should be first exhausted as low as possible and the discharge caused to pass for some time, and as the air accumulates from the electrodes it may be pumped out until a permanently high vacuum is obtained. Sometimes the electric discharge has to be maintained for several hours before a steady condition is reached. The troublesome rise of pressure in a newly exhausted vessel after standing for several hours may in many cases not be due to any leakage in the vessel but to this slow escape of the occluded gases.

31. Making of Air-tight Joints.—As many experiments in this class of work require the fitting together of separate parts of the apparatus so as to be gas-tight a few hints gained by considerable experience in this regard may be of use. In glass vessels it is sometimes required to fit electrodes or more complicated systems so as to be rigid and gas-tight while in place, but in such a way that they may be removed without destroying the apparatus as would be the case of they were sealed through the glass. This is very simply done by the method shown in Fig. 17. Suppose that any object E is to be enclosed in a vessel A so it may be removed at any time later. Turn over the circular edge of A to form a lip all the way round.

FIG. 17.

On a glass tube make a bulb B of the same relative size to the mouth of A as shown in the diagram. Through the opening in the bulb pass the rod supporting E and seal it in the end C. Then B may be placed in the mouth of A and the joint made gas-tight with sealing wax. In making sealing wax joints on glass the glass must first be gently heated till it is hot enough to melt the sealing wax when rubbed over the surface. If the sealing wax be simply melted and dropped on the cold glass it will chip off and be quite useless. When the two glass surfaces to be joined are thus covered with a fairly thick coating of wax gently heat both and press them together and allow to harden. Then any holes may be closed by melting on more sealing wax and very gently heating it till it runs well together. The wax should not be heated to the point of ignition. A perfectly gas-tight and rigid joint may be obtained in this manner. Glass and metal may be easily joined together in the same way.

In the case where two parts of metal or other material fit together fairly closely but are not air-tight and any mechanical strain is borne by the solid parts themselves, paraffin is about as good a material for tightly closing the joint as anything. If the paraffin be carefully melted on a piece of heated metal and run around the opening in a fairly thick coating the joint

may be made perfectly air-tight. This of course is of no use if the apparatus is to be heated above about room temperature. There are several varieties of soft wax which work about equally well for this purpose but paraffin, if clean, has the additional advantage of being a good insulator.

Any metal vessel such as a brass cylinder into which any form of apparatus is to be put and then the cylinder closed and heated to any temperature up to 300° C. or so may be made gas-tight in the following way: Around the opening to be closed attach a metal flange aa as shown in Fig. 17a. This should be attached by brazing, as solder-ing will not of course stand very high tempera-tures. Make a metal plate bb as covering to fit flat on the flange and towards the outer edge pierce both plate and flange with holes so that they may be bolted together. Draw a lead wire down to a diameter of a millimeter or two and place this in a circle on the flange inside the circle of holes, having the two ends which have been shaved down thin overlapping. Ordinary fuse wire serves the purpose admirably. Place the metal plate in position on top of the wire and then tighten the bolts, gradually flattening out the wire till it reaches about one third its original thickness. If carefully done this will make a perfectly tight joint which will stand temperatures where no kind of wax or paste would be of any use at all.
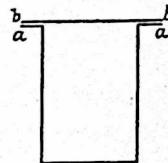
FIG. 17a.

CHAPTER III.

CATHODE RAYS.

32. Some Properties of Cathode Rays. *Phosphorescent Action.*—As seen in § 7 the electric discharge at low pressure causes a stream of minute particles to issue normally in straight lines from the cathode which produce phosphorescence in the glass when they impinge upon it. These cathode rays produce phosphorescence in a variety of substances besides glass. Tubes containing substances showing this action of cathode rays may be obtained already prepared from almost any of the large firms which supply general physical apparatus. If such tubes are available observe the phosphorescence produced in the different substances when the discharge passes. If the discharge tube is made in the laboratory several tubes may be made, each containing in the end remote from the cathode (Fig. 5) a different substance which phosphoresces under the action of the rays. Such substances are different kinds of glass, calc-spar, potassium or barium platino-cyanide, and several of the rare earths such as yttrium, thorium, etc. This phosphorescent property is a very useful one in detecting and observing the rays.

Casting of Shadow.—The rays may be stopped by an opaque obstacle placed in their path. This may be observed by means
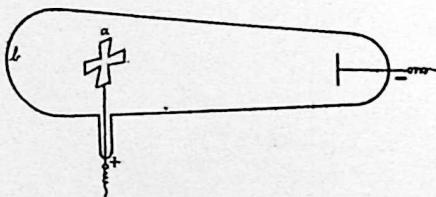
FIG. 18.

of a tube similar to that shown in Fig. 18, in which a piece of metal *a* stands in the path of the rays. The rays falling upon

a are stopped and a distinct shadow is cast on the end of the tube at *b*. Such a tube may be obtained from almost any large instrument firm. This piece of metal is usually hinged at the lower point so that it may be dropped down out of the path of the rays.

With such a tube allow the discharge to pass for several minutes with the cross in the erect position and observe the shadow cast. Then drop the cross out of the way and observe the appearance on the end of the tube. The portion which was originally in complete shadow will now appear to phosphoresce more brightly than the surrounding parts. This is due to the peculiar fact that the glass shows fatigue under the action of the rays and diminishes in brightness while the part which was originally in shadow has not experienced this action of the rays and therefore appears brighter.

Heating Effect.—Make a discharge tube of about 20 or 25 cm. in length as shown in Fig. 19, in which the cathode is concave and spherical in curvature and the anode consists of a piece of platinum about 2 cm. square and from 0.2 to 0.4 mm. thick. This anode should be placed at the center of curvature
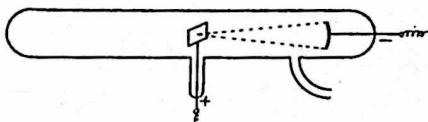
FIG. 19.

of the cathode so the cathode rays may be concentrated upon it. After the tube is pumped down to the proper pressure send a fairly strong discharge through the tube until the anode begins to glow. This glow is the result of the anode being heated by the stream of cathode ray particles bombarding it. The platinum may thus be made incandescent, showing the marked heating effect and energy of the cathode rays.

33. Magnetic Deflection of Cathode Rays.—A discharge tube of the pattern shown in Fig. 20 will be found very suitable for the following experiments. In a tube of from 30 to 40 cm. in length and about 3 or 4 cm. diameter place an alumin-

ium diaphragm about 5 mm. in thickness at the point a at a
distance of a couple of centimeters from the cathode. This
diaphragm should be pierced by a hole about 1 mm. in diam-
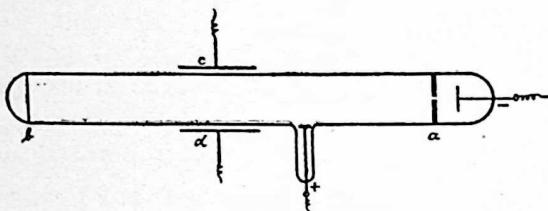
FIG. 20.

eter. Fix in the other end at b a phosphorescent screen of
barium platino-cyanide. A distinct beam of cathode rays will
emerge from the hole in a and produce a phosphorescent
spot on b.

Place the tube between the poles of a moderately strong
electromagnet, the strength of which may be regulated to suit,
so that the magnetic field is perpendicular to the plane of the
diagram. Observe that the bright spot on b will move at
right angles to the direction of the magnetic field. The direc-
tion of motion will depend upon the polarity of the electro-
magnet. Reverse the polarity of the magnet and observe the
spot move in the opposite direction. Determine which is the
north and south poles of the magnet in each case and note
carefully the direction of motion of the spot in relation to the
direction of the lines of force of the magnetic field. Note that
the deflection is in the same direction as would be produced on
a negative charge of electricity moving from the cathode to
the anode.

    34. Electrostatic Deflection of Cathode Rays.—Place two
metal plates of about 3 cm. by 10 cm. on opposite sides of the
tube and parallel to each other as indicated by c and d in
Fig. 20. Apply a steady potential difference to these two
plates of from 500 to 700 volts. This will be best obtained
from a set of three or four hundred small accumulators.
Observe the movement of the spot on the screen. Reverse

the voltage and observe that the spot moves in the opposite direction. Note that the direction is the same as a negatively charged body would move under the action of this electric field in each case. Both the magnetic and electrostatic deflections indicate that the cathode rays are negatively charged bodies moving with a high velocity from the cathode.

35. Cathode Rays Carry Negative Charge.—The negative charge carried by the cathode rays is probably their most important characteristic. This property was originally proved by direct experiment by Perrin and his method was later modified by J. J. Thomson.

A special form of discharge tube is necessary for this experiment and is shown in Fig. 21. This may be made in the laboratory, or any glass-blowing firm will supply it to order.
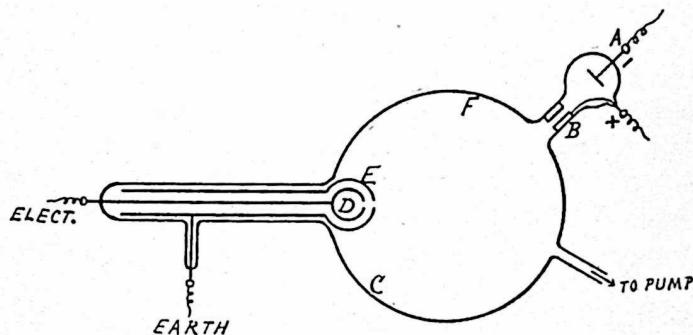
FIG. 21.

CF is a glass bulb from 12 to 14 cm. diameter. A is the cathode and B the anode which should be connected to earth. This anode consists of a brass plug about 1 cm. long pierced by a hole about 1.5 mm. diameter and fitting tightly into the glass tube which may be made a couple of centimeters in diameter. The cathode rays after passing through the hole in B fall upon the wall of the bulb at a point C and produce phosphorescence. Another side tube of 2.5 or 3 cm. diameter which is out of the line of fire of the rays contains two coaxial metal cylinders. The inner one D has a narrow slit in the side as shown and is carefully insulated and connected by a rod

with an electrometer. The outer tube E has a slit opposite that in D and is connected to earth. This shields D and its connecting rod from any stray electrical effects.

Connect this discharge tube to the air-pump and carefully exhaust it until cathode rays appear when the discharge is passing. The discharge may be produced either by an induction coil or Wimshurst machine. The rays will produce a phosphorescent spot at C. Test by means of the electrometer whether D has any charge. It will probably be found that there is a very slight indication of charge on D due to a little stray ionization getting into D, but this effect should be small. Now, using a comparatively strong magnet, bend the beam of rays round until they fall upon the openings in E and D. The movement of the rays may be followed by the phosphorescence they produce. As soon as they fall upon D a sudden charging of the electrometer ought to be observed, showing that D is receiving a charge. Bend the rays still farther round till they miss the opening in D and observe that the charging up of D ceases. Test the electrometer for polarity by a cell to determine whether the charge received by D is positive or negative. The test should show that the charge is negative. This shows that the cathode rays carry a negative charge.

Allow the rays to fall for some length of time on D, and observe that D continues to charge up until it reaches a certain maximum value and will not charge up beyond that value no matter how long the rays continue. This shows that when this state is reached D is losing charge as fast as it is acquired. As will be plain from subsequent experiments this is a result of the gas around D being made conducting by being ionized and thus allowing the charge to leak off as fast as it is acquired after it reaches a certain value.

36. **Velocity and Ratio of the Charge to the Mass of a Cathode Ray Particle.**—Since the cathode rays consist of particles carrying a negative charge and moving with a high velocity it ought to be possible to measure this velocity experimentally and to determine the relation between the mass of a particle and the charge which it carries. The possibility of

deflecting these rays by a magnetic and electrostatic field furnishes a means of determining these quantities.

A special form of discharge tube will be required for this determination. It should be very carefully made by an expert glass blower so that the different parts are carefully lined up and accurately situated relatively to one another. The form of the tube is shown in Fig. 22. The total length of this tube should be in the neighborhood of 60 cm. *C* is a flat
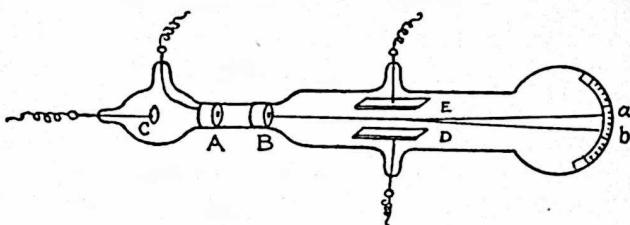
FIG. 22.

cathode from which the rays travel in straight lines. *A* and *B* are thick metal plugs about 2.5 cm. in length and 5 or 6 cm. apart and fitting tightly in the tube of about 2.5 cm. diameter. *A* forms the anode and they are both pierced by holes about a millimeter in diameter which must be in exactly the same straight line so that a very narrow beam of rays may pass along the axis of the tube and fall upon a screen of phosphorescent material at the other end. If the curvature of this end of the tube be small the phosphorescent material may be placed directly on the surface of the glass, but otherwise it may be placed on a flat transparent screen situated just inside the end of the tube. On this screen is a vertical scale in millimeters. Near to *B* are two aluminium parallel plates *D* and *E* about 4 cm. wide and 10 cm. long and from 2 to 2.5 cm. apart.

Exhaust this tube carefully and observe in a dark room the phosphorescent spot produced by the rays on the screen. It is better to use a Wimshurst machine than an induction coil to excite the discharge tube for this experiment as the Wimshurst, if carefully run, will give a more steady current through the tube.

Let v cm. per second be the velocity of the moving particle, m its mass and e the charge it carries in electrostatic units. Let the tube be placed in a strong magnetic field so that the lines of force are perpendicular to the plane of the diagram. The beam of rays will be deflected in a vertical plane so that the spot on the screen will move along the vertical scale from a to b. Let this field be of strength H.

When a field H acts at right angles to an electric current C the force acting at right angles to the plane of the field and the current is $H \times C$. Therefore the force acting along the radius of curvature of the path of the particle tending to deflect the moving charge, which is equivalent to a current equal to ev is equal to Hev. This must be equal to the centrifugal force of the moving particle acting outward along the radius of curvature which from dynamics is equal to mv^2/r, where r is the radius of curvature.

Therefore
$$Hev = \frac{mv^2}{r} \, ;$$

or
$$Hr = \frac{mv}{e} \, . \tag{1}$$

H and r can both be determined as will be shown and therefore mv/e is known.

Now if a difference of potential be established between the two plates D and E a uniform electric field will act on the beam of rays, and if it is applied in the right direction it will tend to deflect the rays in a direction opposite to the magnetic deflection. Let this electric field be X in electrostatic units; then the force deflecting the beam will be Xe. The magnetic field and the electric field may be adjusted so that the deflection produced by one will be just equal to that produced by the other, and if they are in opposite directions the one will just balance the other. Under these conditions, then,

$$Xe = Hev;$$

therefore
$$v = \frac{X}{H} \, . \tag{2}$$

X and H can both be measured and therefore v is determined. Supplying this value of v in equation (1) the value of e/m may be determined.

The magnetic field used to produce this deflection should be as uniform as possible, as the above calculation is made on that assumption. It may be produced by means of an electromagnet of a form similar to that shown in Fig. 23 of which the faces of the pole pieces are plane and about 4 or 5 cm. broad by about 10 cm. in length. These pieces should be just far enough apart to allow the tube to be placed between them. Place the tube between these poles so that the magnetic field is parallel to the plane of the plates D and E. Adjust the current through the coil of the electromagnet till a deflection of the spot of a few millimeters is produced. Apply by means of a set of accumulators a steady voltage to the plates D and E in the proper direction to oppose the magnetic deflection. Adjust this voltage and the magnetic field till the spot returns exactly to its zero position. Then measure H and X.

FIG. 23.

The strength of field H may be measured very conveniently by means of a ballistic galvanometer and a small search coil which may be placed between the poles of the magnet when the discharge tube is removed. From the ordinary theory of the ballistic galvanometer and of currents induced in a coil of known dimensions when suddenly removed from a magnetic field, as given in any text-book on this subject, the number of lines of force per square centimeter, that is H, between the poles of the magnet may be calculated. This should be carefully determined.

X may be measured in volts and then reduced. Supply these measurements in equation (2) and obtain v.

Remove the electrostatic field and observe the deflection ab on the scale. From this and the distance between a and the face of B the value of r may be obtained as follows: Since in any circle the square on the tangent is equal to the rectangle.
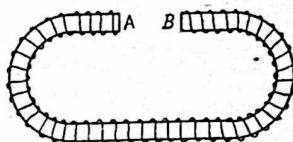
contained by the segments of the secant from the same point
and since Bb is a very short arc of a very large circle to
which aB is a tangent at B, as shown in Fig. 24, therefore bD
may be taken as practically equal to the diameter of the large
circle, and therefore we have

$$aB^2 = ab(ab + 2r).$$

Therefore $$2r = \frac{aB^2}{ab} - ab,$$

from which r is determined by measuring aB and ab in centi-

FIG. 24.

meters. Therefore on supplying the
values obtained for H, r and v in
equation (1) the ratio e/m is obtained.

By the use of this method the aver-
age value of v has been found to be
2.8×10^9 cm. per second. This value
is not quite constant, as it varies some-
what with the fall of potential in the
discharge tube. The value of e/m
has been determined a great many
times and by different methods, and
the latest determinations give the value as 1.7×10^7.

**37. Comparison of e/m for the Cathode Particle with that
for the Electrolytic Ion.**—In the conduction of electricity
through a solution the electrolytic ions which are set free by
electrolysis carry an electric charge and the ratio of this charge
to the mass of the ion may also be determined. Take the case
of the hydrogen ion and let M be its mass in grams and E the
charge which it carries. Since 1.0357×10^{-5} is the electro-
chemical equivalent of hydrogen it requires one coulomb of
electricity to liberate 1.0357×10^{-5} grams of hydrogen from
a solution. Therefore it requires 96550 colombs, or 9655
electromagnetic units of electricity, to liberate one gram and
$9655 \times M$ units to liberate M grams or one ion. Therefore
the hydrogen ion in its migration through the solution must
have carried a charge of $9655 \times M$ units, and therefore
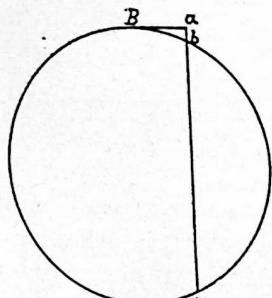
$E = 9655 \times M$ and we have $E/M = 9655$, which is very approximately 10^4. Since hydrogen has the smallest atomic mass known this ratio for hydrogen is the largest such ratio known in electrolysis.

By comparison then the value of e/m for the cathode ray particle is 1700 times the value of E/M for the hydrogen ion or atom. In a later chapter the value of e will be determined and it will be found to be equal to the value of E for hydrogen. It follows then that the mass of the cathode ray particle is 1/1700 of the mass of the hydrogen atom. The cathode ray particle possesses the smallest mass yet known and it is variously called by the name of negative "corpuscle," negative "ion" or electron.

38. Lenard Rays.—It was long considered impossible for cathode rays to pass through any solid material. Hertz was the first to disprove this and he showed that if the rays fell upon very thin aluminium foil or gold leaf a distinct phosphorescence on the other side of the foil was produced which could be deflected by a magnet. Later Lenard made a very thorough investigation of this question. The following experiments which may be performed in the laboratory will illustrate the methods which he employed. Make a discharge tube of the form shown in Fig. 25. TT_1 is a glass tube about 20 or 25 cm. in length and from 4 to 5 cm. in diameter. C is a flat aluminium cathode supported by a stiff aluminium wire and this wire is completely surrounded by a small glass tube ab which is sealed at b around a platinum connecting wire in the usual way. This may very easily be fitted into the larger tube TT_1 by joining a short tube d, into which ab just fits, to the larger tube as shown. The opening between ab and d may then be closed by sealing wax. AA is the anode which consists of a metal cylinder about 3 or 4 cm. long surrounding ab and whose support passes out through a side tube f. The end T_1 of the large tube should be carefully ground flat so as to fit on a plane surface. Close this end by a brass plate about 1 mm. thick and seal it to the tube with sealing wax or marine glue. Through the center bore a hole about 1.5 mm. in diameter.

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Cover the hole with a sheet of thin aluminium foil in the
neighborhood of 0.002 mm. in thickness and carefully seal it
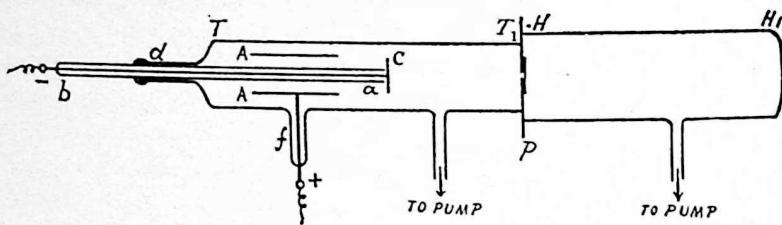
FIG. 25.

down. HH_1 is a glass tube about 15 cm. long with the end H
ground flat to fit the plate and sealed to it by wax or glue.

Connect the plate P and the anode to earth and exhaust the
tube TT_1 until a powerful discharge of cathode rays is pro-
duced. Observe in a dark room the phosphorescence in HH_1
around the aluminium window in P. Observe that when the
air in HH_1 is at atmospheric pressure this phosphorescence
extends only a short distance beyond the window. Now
gradually exhaust the tube HH_1 and observe that as the pres-
sure is lowered the rays extend farther into the tube, until,
when a very low pressure is reached, a well-defined beam of
rays extends along the tube. Bring a magnet near this beam
and observe the deflection of the rays.

If a phosphorescent screen with a scale similar to that in the
tube of Fig. 22 be placed in the end H_1 of the tube HH_1 and a
magnetic and electric field be applied to the beam of rays the
velocity of these rays and the ratio e/m may be determined by
the same method as was described in § 36 in the case of cathode
rays. Lenard measured these quantities and found that these
rays were transmitted with a somewhat higher velocity than
ordinary cathode rays, but that the ratio e/m was the same as
for cathode rays. These rays beyond the aluminium window
act in all respects like cathode rays. They are identical with
cathode rays, but since they are produced outside the cathode
ray tube they are usually called Lenard rays to distinguish
them from those produced inside the tube.

39. Canal Rays.—Goldstein, in working with a highly exhausted tube, found that if he used a perforated cathode instead of a solid one luminous streams emerged through the holes in the cathode in the direction opposite to the cathode rays. These rays have been called Canalstrahlen or canal rays. They produce phosphorescence and they may be deflected by a magnetic and an electric field, but the deflection is much less than in the case of cathode rays, and it requires extremely strong fields to produce the deflection. The direction in which they are deflected is opposite to that for the cathode rays which indicates that they are positively charged particles. The velocity and the ratio of e/m for these particles have been determined. It is found that they travel with a smaller velocity than that of cathode rays. The ratio e/m is not constant as in the case of cathode rays, but shows a considerable variation under different conditions. The maximum value found was about 10^4, which, as we have seen, is the ratio of E/M for the hydrogen ion in electrolysis. This indicates that the mass of these positive ions is at least of the same order as the mass of the hydrogen atom. The positive ion therefore appears to be atomic in size and is at least about 1700 times the mass of the negative ion produced in a gas at low pressure.

These rays may be observed by using a discharge tube of the form shown in Fig. 26. It may be easily made from a glass
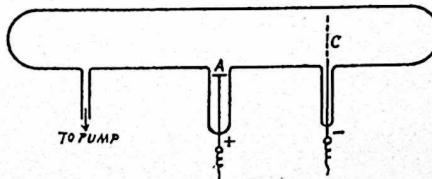
FIG. 26.

tube about 2.5 cm. in diameter and 25 cm. long. The cathode C consists of a flat aluminium disk whose support passes through a side tube so that it may be out of the way of the rays. The disk C is perforated by a number of holes about 1 to 1.5 mm. in diameter.

Exhaust this tube and when the pressure is in the neighborhood of that required for the production of cathode rays pass a discharge through it and carefully watch in a darkened room, as the pressure is gradually lowered, for the appearance of the luminous streams emerging from the holes on the side of the cathode remote from the anode. Observe the phosphorescence produced on the glass. Apply a strong magnetic field and also an electrostatic field to the rays and note the deflection which results in each case and the direction of this deflection.

CHAPTER IV.

RÖNTGEN RAYS. (DESCRIPTIVE.)

40. Origin of Röntgen Rays.— The negatively charged cathode ray particle travelling with such a high velocity must possess considerable kinetic energy. Sir J. J. Thomson has shown mathematically that when a rapidly moving electric charge is suddenly brought to rest an electromagnetic disturbance is produced in the surrounding medium and it travels outward from the suddenly arrested particle. This condition is fulfilled when a cathode ray particle is suddenly stopped by striking against a solid body. In the year 1895 Röntgen observed, in working with an ordinary cathode ray tube, that some sort of radiation was produced outside the tube. Phosphorescent bodies placed outside the tube were strongly excited and a photographic plate in the neighborhood became blackened. These radiations differ in many ways as we shall see from cathode rays and have been called Röntgen rays after their discoverer. The name first applied to them was X rays and this name is still commonly used. They travel in straight lines with very high velocity. This velocity of propagation has been measured by Marx and found to be the same as the velocity of light, namely 3×10^{10} cm. per second.

41. Röntgen Ray Focus Tube.—For purposes of experimental study and the practical application of Röntgen rays they are produced by means of a particular form of discharge tube which is usually called a focus tube. This tube takes several modified forms, all of which however conform to the same general principle, which is shown diagrammatically in its simple form in Fig. 27. This simple type of tube will serve the purposes of all the experiments described in this chapter in which no quantitative measurements are required. If however the automatic form which will be described in the next chapter is available it will serve the purpose even better for these experi-

ments. *AB* is a large glass bulb anywhere from 15 to 20 cm. in diameter with the two electrodes *a* and *b*. The cathode *a* consists of a spherical concave piece of metal usually aluminium. The cathode rays proceed normally from the surface of *a* and on account of its spherical shape are brought to a focus at the point *c* on the anode *b*. This anode in its simplest form consists of a flat platinum plate placed at an angle of 45° to
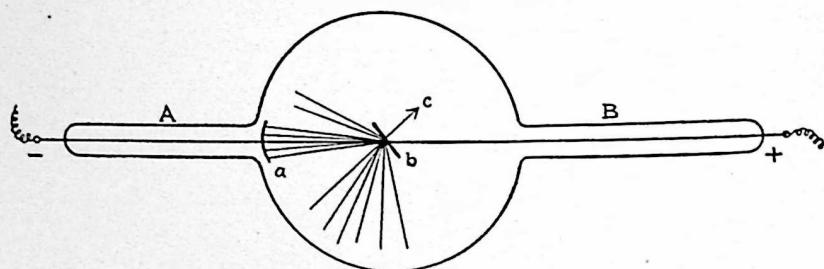
FIG. 27.

the axis of *a* and so that the centre of *b* is at the point *c*. The cathode rays are thus brought to a focus at the centre of the anode, and hence the name focus tube. The electromagnetic pulses or Röntgen rays therefore have their origin at the anode *b* and travel outward in all directions.

To generate the rays the electrodes are connected to the terminals of the secondary of an induction coil or to a Wimshurst machine. The discharge must of course be sent through the tube in the right direction so that *a* is the cathode. This is easily determined by the appearance of the discharge, for when the direction is correct the half of the bulb towards *a* cut off by the plane of *b* will be clearly defined by the phosphorescence produced by the Röntgen rays falling upon the glass in that half of the bulb while if the discharge is in the reverse direction the phosphorescent illumination will be very irregularly distributed.

The following experiments should be set up and performed in a room which may be completely darkened so as to facilitate the observation of the phosphorescent and photographic action.

42. Phosphorescent Action of Röntgen Rays.—One of the earliest observed properties of Röntgen rays was their phosphorescent action on certain substances. This is easily observed by the phosphorescence produced in the glass by the rays falling upon the inside of the bulb as mentioned above. This phosphorescence may be observed in a great variety of solid substances such as the double sulphate of potassium or uranium, crystals of willimite, platino-cyanide of barium and quite a number of compounds of the alkali metals. Obtain specimens of as many of these substances as possible and allow the Röntgen rays to fall upon them in a darkened room and observe the luminescence produced in each case. Note the differences in color and intensity of the phosphorescence in the various substances.

A screen made of one of these substances will be found very useful and almost essential in many qualitative experiments on Röntgen rays for detecting the presence of the rays and noting differences in intensity, etc. Such a screen may be made by taking a thin sheet of white bristol-board 30 cm. square and dusting a uniform and fairly thick coating of fine crystals of platino-cyanide of barium over the surface which has been made adhesive by a thin coating of paste. This should be mounted in a frame. Such screens may be obtained from any scientific instrument maker who deals in Röntgen ray apparatus.

43. Penetrating Power of Röntgen Rays.—Röntgen rays differ in a very marked degree from cathode rays in the fact that they are able to penetrate bodies of considerable thickness, while we have seen that cathode rays can not. Their penetrating power, as well as some of their other properties, depends upon the conditions existing within the Röntgen ray bulb. With a very low pressure within the tube, and consequently a large potential difference between the electrodes, the rays produced possess considerable energy and are very penetrating, being capable of going through several centimeters of wood and even several millimeters of a dense substance like lead. Such rays are usually called "hard rays" and the bulb from which they are produced is often termed a "hard" bulb. In

the case of a higher pressure and consequent smaller difference of potential the rays are less penetrating and are called "soft rays." A Röntgen ray bulb of the simple type described in § 41 will usually become "hard" after being used for a considerable time, owing to the fact that at these low pressures the long-continued passage of the discharge seems to drive the gas into the walls of the bulb and thus lowers the pressure. The gas may be driven out of the walls again by very carefully warming up the bulb slightly from outside.

If two bulbs are available, one a "hard" and the other a "soft" one, compare approximately the relative penetrating power of the rays from the two bulbs as follows: Allow the rays from each of the bulbs in turn to fall upon the fluorescent screen and note the intensity of illumination in each case. Now place in the path of the rays a sheet of wood of one or two centimeters in thickness and observe by means of the screen that the intensity is cut down more by the wood in the case of the soft rays than in the case of the hard rays. This may also be tried with many other substances such as thin sheets of aluminium, brass or lead.

Different substances absorb rays of any particular type to a different degree. Generally speaking the denser substances produce the greater absorption. Metals absorb the rays more than such materials as wood and glass, and even the metals differ widely among themselves in this respect. Aluminium, for instance, allows a much greater proportion of rays to pass through it than does the same thickness of lead.

Using a bulb of medium degree of "hardness" test the absorbing power of different substances as follows: Procure specimens of different materials such as aluminium, brass, zinc, lead, wood, glass, cardboard, mica, etc., in the form of sheets about a millimeter or two in thickness and about 3 cm. square. These specimens should all be of the same thickness. Arrange four or five of them side by side in the same plane by means of a frame or otherwise and place them in the path of the rays between the bulb and the phosphorescent screen, so that the rays fall perpendicularly upon and pass

through all the specimens simultaneously. Observe the difference in intensity of the rays as shown by the screen after passing through each of the specimens. Repeat this for all the specimens at hand and note carefully the difference in their power of absorption.

The amount of absorption produced in a given type of rays depends of course upon the thickness of the absorbing material. Procure several specimens of sheet aluminium varying in thickness from about .1 mm. to 5 or 6 mm. Arrange these as in the previous experiment so that the rays fall upon them simultaneously, and observe the absorption produced by the different thicknesses of the same material. Repeat this with a set of specimens of sheet lead and also any other substance available.

This difference in the absorbing power of different substances is well illustrated in the case of parts of the human body. Place the hand or arm close up against the phosphorescent screen between the screen and the Röntgen ray bulb. Observe the comparatively dim outline of the flesh and the well-defined outline of the bones, which is due to the fact that the flesh absorbs the rays only to a small extent while the bones absorb them much more. The latter thus casts a much deeper shadow than the former. It is by this means that any foreign substance, such as a bullet, may be located within the body by means of the Röntgen rays, as such a substance will cast a deeper shadow than the surrounding parts of the body.

44. Use of Lead as a Screen from the Rays.—It will be observed in the above experiments that lead absorbs the rays to a greater extent than any of the other substances. This great absorbing power of lead serves a very useful purpose in screening anything from the action of the rays. It is usually of advantage and very often necessary to work with a well defined beam of rays. Since the Röntgen ray bulb gives out rays extending over a large area it becomes necessary, in order to obtain a well defined beam, to screen off a large proportion of the rays and use only those travelling in a given direction. This is done by placing in front of the bulb a large thick sheet of lead with a well defined hole of the proper size cut in the

sheet exactly opposite the anode of the bulb. Only the rays which emerge from this hole are available for observation and the extent of this beam is regulated by the size and shape of the hole. Before proceeding farther with any experiments on Röntgen rays a permanent screen should be set up in a convenient place where it will not require to be moved.

Make a strong wooden box at least 3 or 4 feet square. If space will allow, an even larger one will be found convenient. Make one whole side of the box to open on hinges as a door. Carefully cover the box on all six sides with sheet lead about ⅛ inch thick, being careful that there are no openings at the joints of the lead. Set this box up beside the table on which the rest of the apparatus is to be arranged. In the side of the box facing the table cut, at a convenient height, a hole about 8 cm. square. On the inside of the box opposite the opening set up the Röntgen ray tube, carefully placing it so that the anode faces the opening and the axis of the tube is horizontal and parallel to the face of the box. This may be done conveniently by placing two wooden brackets on the wall of the box, one on either side of the opening and placing on each of these an insulating block of paraffin cut out to fit the tubes A and B (Fig. 27), which rest on these blocks. When carefully adjusted firmly fix the tube to these blocks by running a little melted paraffin around the place of contact. Care must be taken in doing this so as not to crack the tube by the hot paraffin.

Place inside this box also the induction coil or Wimshurst machine and all their connections by which the bulb is to be run. Make connections from the induction coil to the X ray bulb by means of very fine double covered wires, not larger than about No. 32, as heavy wires are unnecessary and are apt to put a strain on the different parts of the bulb. Be very careful that these wires do not come in contact with the glass of any part of the tube, for if they do the glass is apt to be punctured by a spark. Besides serving as a screen to control the beam of Röntgen rays this lead-covered box serves to screen off from the testing and measuring apparatus all electro-

static disturbances which might be caused by the induction coil and connections. All the different sections of this lead covering should be carefully soldered together and connected to earth. This screening and earth connection is very important to insure favorable conditions for working. A neglect of this is very often the cause of trouble in this class of work.

In order to secure a beam of rays of any desired shape or area of cross section it will be found convenient to cut a sheet of lead of the same thickness as used in covering the box and about 25 cm. square, and arrange on the face of the box a pair of grooves into which this sheet may slide so as to cover the opening in the box. In this sheet a hole of the desired size and shape may be cut. A number of such interchangeable screens may be made to suit the different requirements in each case. These screens should fit closely to the face of the box so that no stray rays may escape around the sides.

45. Photographic Action of Röntgen Rays.—When Röntgen rays fall upon a photographic plate they produce an effect exactly similar to that of light. The effect produced depends upon the intensity of the rays and the length of time of exposure. Consequently if the intensity has been diminished by passing the rays through an absorbing material before reaching the plate the effect on the plate will be diminished. The difference in the absorbing power of different materials thus enables us to make Röntgen ray photographs. For instance, photographs of the interior of different parts of the human body may be made as shadows if these were thrown on the phosphorescent screen as in § 43. Röntgen ray photographs differ from light photographs in the fact that the latter are produced by reflection of the light from the object photographed, while Röntgen ray photographs are produced by the rays after passing directly through the object.

Wrap up a photographic plate in black paper so as to exclude any light. This of course does not prevent the action of Röntgen rays, as they will penetrate the paper. Place this enclosed plate a foot or two in front of the X ray bulb. Place the hand close to the plate between the plate and the bulb.

Allow the rays to act for 15 or 20 seconds. This time will depend greatly upon the strength of the rays and will have to be tested by a preliminary trial for the particular bulb used. Develop the plate in the ordinary way and observe the impression produced.

On a thin board about 3 or 4 mm. thick fasten various objects, such as discs of metal or coins of different kinds and different thicknesses and objects of various shapes. Place this set of objects in the path of the rays and take a photograph of it. Note carefully the difference in the absorption by the different objects as shown by the difference in the intensity of the shadows cast.

46. Conductivity of Gases Produced by Röntgen Rays.— Probably the most striking property of Röntgen rays is their power to cause gases to become conductors of electricity. As before mentioned, gases under normal conditions of temperature and pressure and under ordinary voltage are almost complete non-conductors of electricity. If a well insulated body such as the leaves of a gold leaf electroscope be charged up in thoroughly dry air the charge will be retained for many hours. There may be an extremely slow diminution of the charge on the gold leaves due in part to the want of perfect insulation and partly due to a very small leakage through the air. If however a beam of Röntgen rays be allowed to pass through the gas surrounding the leaves they will immediately lose their charge and collapse, showing that the charge must have leaked away through the air.

Set up an electroscope, of the form described in § 22, Fig. 14, at a distance of 25 or 30 cm. in front of the window of the lead box containing the Röntgen ray bulb. Charge up the leaves by storage cells to a fairly high positive potential, and if the insulation is good the leakage of the charge should be extremely small. Start the X ray bulb and allow the rays to fall upon the air in the electroscope. Observe the sudden collapse of the leaves.

Now by means of a lead screen without any opening in it placed over the window cut down the intensity of the rays to

a small fraction of their original intensity and also adjust the position of the electroscope so that a well defined beam of rays passes through only the lower portion of the electroscope as far away from the leaves as possible. Recharge the leaves and start the rays again, and if the intensity has been cut down sufficiently the leaves should collapse at a very much slower rate than before. Charge up the leaves with a negative charge and repeat the experiment. Observe that the discharge takes place just as before and at just the same rate as in the case of the positive charge.

These experiments show that the air has become conducting under the influence of the rays and discharges electricity of either sign with equal facility, and the conductivity depends to some extent at least on the intensity of the rays. By interposing screens of different thicknesses the dependence of the conductivity on the intensity of the rays may be noted by observing that the less the intensity of the rays the slower the rate of leak shown by the leaves.

47. Transportation and Persistence of Conductivity.—Arrange a scheme of apparatus as shown in Fig. 28. *AB* is a
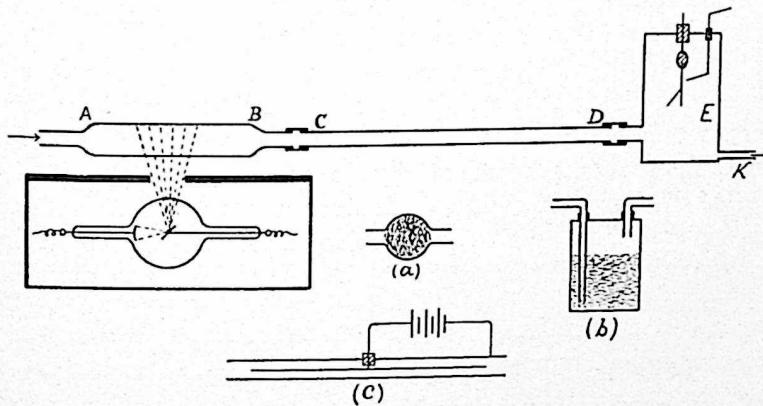
FIG. 28.

thin brass tube about 12 cm. long and 4 or 5 cm. in diameter placed as shown in front of the window of the Röntgen ray enclosure. It is joined by a temporary joint of large rubber

tubing or other convenient means to a brass tube CD about 30 or 40 cm. long and 3 cm. diameter. This is joined at D by a similar temporary joint to the tube leading into the electroscope E. Connect the metal parts all to earth. A current of air may be slowly drawn through the whole system entering at A and leaving at K by an aspirator attached to the outlet K.

Charge the leaves of the electroscope. Start a slow current of air through the system and note that the leaves still retain their charge. Now start the X ray bulb with the current of air still flowing and observe that the leaves immediately begin to lose their charge. This indicates that the conductivity imparted to the air in AB may be conveyed by the current of air to the electroscope at a considerable distance away and that it lasts long enough at least to be carried that far. Stop the rays and the current of air and recharge the electroscope. Start the X ray bulb again without any current of air flowing through the system and observe that there is now no leakage of the charge from the leaves. This shows that it requires an air current or some such means to transport the conductivity from where it is produced in AB to the electroscope.

Again recharge the electroscope and run the bulb for five or ten seconds without any current of air passing. At the end of that time stop the bulb and after two or three seconds start the current of air and observe the slow discharge of the leaves. Repeat this but after stopping the bulb wait for a slightly longer interval before starting the air current and note that the rate of discharge of the leaves is not quite so rapid. Repeat this several times, each time waiting a longer interval after stopping the rays before starting the air current and observe the gradual diminution of the rate of leak until finally if the interval is long enough no leak takes place at all. These experiments indicate that the conductivity imparted to the air by the rays persists for a short time after the rays have ceased. It does not last indefinitely but gradually disappears.

48. Removal of Conductivity.—Between B and C at the joint BC insert a glass bulb a filled with cotton wool, not too closely packed. Start the current of air and also the Röntgen rays and observe the effect on the electroscope. It should show

no leakage of the charge from the leaves, showing that the air
in passing through the cotton wool loses its conductivity.

Remove the bulb *a* and substitute for it a wash bottle *b*
partially filled wtih water and repeat the last experiment.
Again there should be no discharge of the electroscope, indi-
cating as before that the air loses its conductivity by bubbling
through water.

Remove the wash bottle *b* and also the tube *CD* and in its
place substitute the brass tube *c*, which has about the same
dimensions as *CD*. Along the central axis of this tube there
is a stiff wire supported and insulated by an ebonite plug.
When this tube is in place it should be insulated from both
AB and the electroscope. Connect the central wire to one
pole of a battery of small accumulators and the tube to the
other pole, so that there is a field of about 150 volts between
the wire and the tube. Now start the Röntgen rays and also
the current of air and observe whether there is any leakage
from the gold leaves. They should show no leakage. Discon-
nect the battery from the wire and the tube and connect them
to earth while the Röntgen rays and the air current are still
running and observe that the leaves immediately begin to lose
their charge. Put the electric field on to the tube and wire
once more but in the reverse direction to what it was before
and observe that the discharge in the electroscope ceases. The
conductivity of the air is thus removed by passing through a
strong electric field.

49. These experiments show that when Röntgen rays pass
through air it becomes a conductor of electricity and this con-
ductivity imparted to the air by the rays persists for a short
time after the rays cease to act on the air, but gradually dis-
appears. While it lasts it may be transported from one point
to another along with the air. This conductivity must be due
to something mixed with the air, for it is removed by the
passage through the cotton wool and the water, and its removal
by the electric field also indicates that whatever is mixed with
the air to produce this conductivity must be charged. In the
following chapter we shall discuss the full significance of these
phenomena,

CHAPTER V.

50. In this chapter we will investigate the properties of Röntgen rays more in detail, especially the property of imparting conductivity to gases, and discuss the methods of making quantitative and more precise measurements on the rays.

51. Automatic Focus Tube.—The nature of the rays and the effects which they produce depend to a great extent upon the conditions existing within the X ray bulb. The amount of conductivity produced, for instance, depends upon whether the rays are "hard" or "soft." In making definite quantitative measurements any variation in the nature of the rays is therefore fatal to any attempts at accuracy.

The chief source of difficulty in the use of Röntgen ray bulbs is the tendency for the pressure within the bulb to change, owing to the passage of the discharge through it. When the discharge is continued for some time the pressure becomes less as the gas seems to be driven into the walls and other parts of the tube. The rays then become more penetrating. Also by the bombardment of the platinum anode by the cathode rays it becomes heated and this heating of the anode liberates the occluded gas, which increases the pressure. This tends to soften the rays. These two sources of change do not counterbalance each other, and consequently the simple form of bulb described in § 41 is irregular in its action as regards the type of rays which it gives out and is consequently not suited to quantitative measurements. Various methods have been tried to overcome this difficulty, but the most successful ones are those which have resulted in the automatic regulating tube. One form of this is shown in Fig. 29, in which AB is the main bulb of the usual form. To this is attached a small side tube ab, with two electrodes, in which is placed in some cases a little powdered caustic potash while in others one of the electrodes

has mica sheets attached. The anode of this small tube is attached to the anode of the main bulb, while the cathode has a wire W attached, and between this wire and the main cathode is a spark gap H. When, by the continued passage of the discharge through the main bulb, the pressure becomes less and the resistance between the main electrodes consequently greater the discharge will then pass across the spark gap, if it is short enough to make its resistance sufficiently small, and through the small tube ab. The heat of the discharge through ab will liberate vapor from the caustic potash or the mica
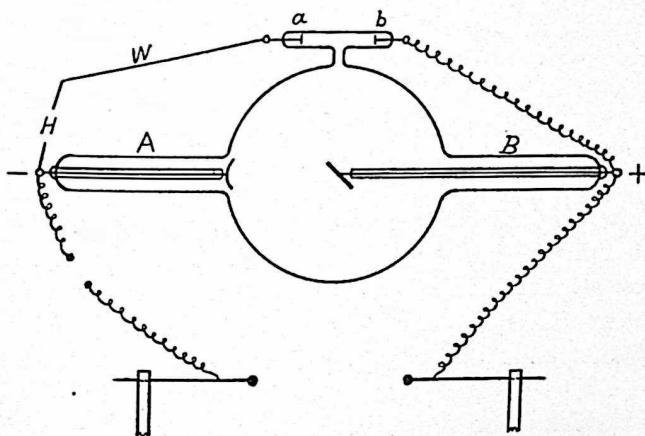
FIG. 29.

which will raise the pressure in the whole system and lower the resistance and allow the discharge to pass through the main bulb again. It will continue to pass through AB until the pressure becomes too low again, when it will once more pass through ab. The pressure is thus automatically regulated. The longer the spark gap H the lower will the pressure in AB become before the discharge will pass across H and through ab. Therefore by adjusting the length of the gap H the bulb may be made to work at any desired pressure within certain limits. The longer the spark gap the "harder" will be the

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rays produced. This type of bulb is very regular in its action and gives very satisfactory results.*

A somewhat modified and improved type on the same, principle is shown in Fig. 30. In this a side tube K, containing a chemical which gives off vapor when heated and absorbs it
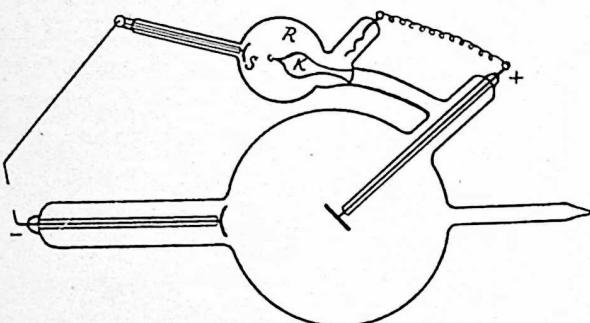
FIG. 30.

again when cooled, is directly connected to the main bulb. It is surrounded by another tube R which is exhausted to a low Crookes' vacuum. In this form the pressure in the main bulb is very low to start with and it has therefore a very high resistance, and at the start the discharge will pass over the path of least resistance across the spark gap and through the tube R which is at a low vacuum. The bulb K is directly opposite the cathode S in this tube and the bombardment by the cathode rays will heat K and liberate vapor from the chemical contained in it. This will continue till sufficient vapor has been liberated to raise the pressure in the main bulb so that the resistance is low enough to allow the discharge to pass through it instead of through R. When the discharge through R thus ceases the chemical in K will cool down and absorb some of the vapor which will lower the pressure in the main tube again. This will be adjusted again by the discharge passing through R once more and heating K and liberating more vapor. This side tube attachment thus automatically

* This type of bulb may be obtained from various manufacturers of X ray apparatus.

regulates the pressure in the main bulk. The pressure at which the tube works will depend upon the resistance across the spark gap and through the side tube, that is on the length of the spark gap. The working pressure may thus be regulated by adjusting the length of the spark gap.

The difficulty caused by the heating of the anode by the impact of the cathode rays is usually best overcome by making the anode of a large piece of platinum so that there is a large mass to heat and consequently less rise of temperature. The anode is also sometimes supported by a copper stem as the copper conducts the heat away more rapidly. In some forms there is a water-cooling arrangement attached to the anode but this is not very satisfactory.

52. Setting up and Manipulation of Röntgen Ray Bulb.— In starting to use an X ray bulb without any previous experience great care should be exercised as it presents certain conditions which are not met with in connection with common electrical apparatus. Although a number of rules can be laid down for the general use of an X ray tube, still rules can not be given to cover every contingency which may arise and a complete knowledge of the action of X ray bulbs can only be gained by experience. A few general hints in this regard may be of value.

Set up carefully the automatic focus tube in the lead box as explained in § 44. Avoid any strain on the bulb. Use fine double covered wire, not larger than about No. 32, to connect the electrodes of the bulb to the terminals of the induction coil, as heavy wires are apt to cause a strain on the bulb which is liable to result in a crack. Do not under any circumstances allow these wires to touch the glass parts of the tube or to come any nearer to the glass than is really necessary, for a spark is liable to pass from the wire to the glass and cause a puncture of the glass and ruin the tube. Connect the negative terminal of the induction coil or static machine to the cathode of the bulb and the positive terminal to the anode of the main bulb and automatic regulator. Careful attention should be given to this to ensure that the discharge

passes in the right direction through the bulb. When the discharge is in the right direction the following observations will aid in making certain of it: (1) When the main bulb lights up the half of the bulb opposite the face of the anode should be uniformly phosphorescent while the half behind the anode should be comparatively dark. If the discharge is in the wrong direction the illumination will be irregular. (2) A shadow of the anode should be cast by the cathode rays on the bulb on the side directly opposite the cathode. If the discharge is in the wrong direction this will not appear. (3) A tube running correctly will cast a well-defined shadow of any object on the fluorescent screen, while if the discharge is in the wrong direction the illumination on the screen will be faint and the shadows indistinct.

If the current is sent through the bulb in the wrong direction it causes platinum to be given off from the platinum anode, which is deposited on the walls of the tube and blackens the tube. When an induction coil is used to drive the bulb there is always a certain amount of reversal current which is injurious to the bulb. This may be eliminated to a great extent by placing a spark gap between one of the terminals of the coil and the electrode of the tube instead of connecting both terminals directly to the tube. The length of this spark gap can be adjusted by trial so that the spark passes without difficulty.

The type of automatic make and break used in connection with the induction coil is of great importance in securing uniformity of action of the Röntgen ray bulb. The ordinary form of spring hammer brake attached to coils is not at all suitable, especially for large coils, for the contacts gradually fuse and their action does not remain uniform. A Wehnelt interrupter, or motor-driven rotary mercury interrupter, or some such uniformly running type gives much more steady action in the bulb and is much more satisfactory.

Start the bulb up carefully with a spark gap of from 2 to 5 cm. After it is started this may be regulated to any desired length, depending upon the type of rays required. Knowledge

of this can only be gained by experience and definite rules cannot be laid down for definite lengths of spark gap.

To keep a bulb in good condition never run it continuously for any considerable length of time as the parts are apt to become heated and conditions change. When making quantitative measurements it is best to run it not more than from twenty to forty seconds without a stop unless the experiment really demands a longer run.

53. General Hints on Making Measurements.—Notwithstanding the great improvements in Röntgen ray bulbs and their adjustments there is still apt to be considerable want of uniformity in the results produced unless certain precautions are taken in the use of the bulb. When taking a series of quantitative measurements on the conductivity produced by Röntgen rays the first precaution to be observed is to run the bulb regularly, that is, run it for equal times and allow equal intervals of rest between the runs. The bulb does not always start up at full strength immediately on starting, therefore it should be run for a preliminary five seconds or so before starting to take any reading on the electrometer or other measuring instrument.

In making measurements a single reading or observation can never be relied on alone, as might be done in some other electrical measurements, on account of the want of perfect constancy of the rays. The readings should always be repeated two or three times at least and in some cases more, and an average of the readings made. Judgment will have to be used as to the number to be taken according to the agreement shown among the readings.

In making comparative measurements with the electrometer the readings should, as far as possible, be made over the same portion of the scale to avoid inaccuracies in the scale and also errors due to the difference of angle at which the beam of light falls upon the scale at different points.

When a series of measurements are being taken with the electrometer its sensitiveness should be tested at intervals during the measurements to ensure that it is not changing,

or if it is changing to furnish a means of correcting for the change and reducing all the readings to the same basis.

The electrometer should be set up ready for use in the manner described in Chapter II in a convenient permanent position near by the lead box containing the Röntgen ray bulb, so that it may be connected to any apparatus set up in front of this box.

54. Production of Current Through the Air by Röntgen Rays.—Cut two plates of aluminium about 15 cm. square and set them up on edge on clean paraffin blocks so that they stand vertical. Place these plates parallel to each other about 6 or 8 cm. apart and 8 or 10 cm. in front of the window of the Röntgen ray enclosure so that a beam of rays from the bulb S will pass between them as shown in Fig. 31. Over the window place
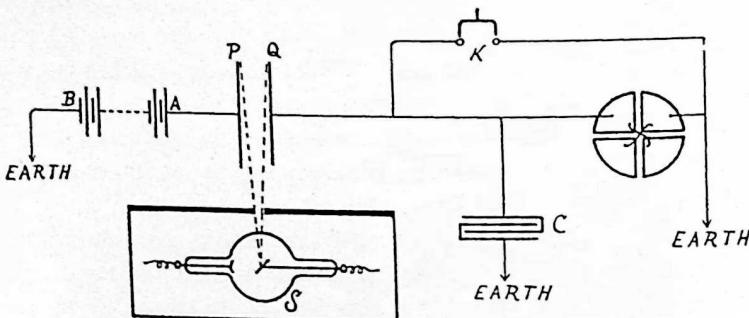
FIG. 31.

a thick lead screen with a rectangular hole cut in it about 1.5 cm. broad and 6 cm. high so that this hole is directly opposite the center of the anode of the bulb. Arrange the plates P and Q symmetrically with regard to this opening. These dimensions are only given as a guide, but the exact width of the hole and the distance apart of the plates and their distance from the hole must be carefully arranged so that the cone of rays from the bulb will pass between the plates without touching their surface. This can be tested experimentally by holding the fluorescent screen just in front of the plates and noting the width of the illumination on the screen which should be just a little less than the distance between the plates.

To one plate P connect the positive pole A of a battery of small accumulators of 20 or 30 volts, while the negative pole B is connected to earth. Connect the other plate Q to one pair of quadrants of the electrometer through a screening tube (§ 14), the other pair of quadrants being connected to earth. Connect in parallel with Q an adjustable condenser C as indicated. Also make a connection to earth through the special electrometer earthing key K (§ 16) which is worked by a cord at a distance.

Close the earthing key K, adjust the condenser to a capacity of about 0.5 microfarad and start the bulb. After running for two or three seconds open the key K. Note that the electrometer needle immediately begins to indicate that the quadrants connected with Q are receiving a charge. If the movement of the needle is too rapid increase the capacity of the condenser, or if too slow decrease it. Observe that this charging up continues as long as the rays continue to act. Stop the rays and the charging up will cease. Earth the plate Q again through K and reverse the connections of the battery so that P is connected to the negative pole B and A to earth. Repeat the last experiment and note that the needle indicates that Q receives a charge of opposite sign as the movement is in the opposite direction. Stop the rays and close K and then test the electrometer with a standard cell as to the sign of the charge indicated by the movement of the needle in either direction (§ 17). The test should show that in the foregoing experiment when P was connected to the positive pole of the battery while the rays were acting the plate Q received a positive charge, while when P was at a negative potential Q received a negative charge.

After making a number of preliminary trials of this nature carefully regulate the sensitiveness of the electrometer needle by adjusting the potential on it and also adjust the capacity C until the electrometer needle shows a movement of about five scale divisions per second. This can also be regulated to some extent by adjusting the intensity of the rays by placing a metal screen in front of the window to cut down the intensity. After

a convenient rate of movement of the needle is obtained the rate at which the plate Q charges up can be measured, as the rate of charging up is proportional to the rate of movement of the needle, that is to the number of scale divisions passed over per second. This rate may be measured with a stop watch. Having made this adjustment repeat the above experiments and observe carefully by a stop watch the time taken for the spot of light to move over a given distance on the scale. Take several readings first in one direction and then reverse the connections of the battery and take several in the opposite direction. Take the average in each case and the same average reading should be found for the two directions. Make a number of such observations so as to become perfectly familiar with the method.

These experiments indicate that the rays in some way cause a transference of electricity from the air to the plate Q and the sign of the electric charge given to Q depends upon the sign of P. The quantity of electricity transferred per second is the same whether it is positive or negative. There must be, in other words, a current of electricity through the air between P and Q and the current is of the same magnitude whether P is positive or negative with regard to Q. The direction of the current depends upon the sign of P with regard to Q.

55. Variation of Current with Voltage.—Connect the plate P to a potential of only 2 or 3 volts and measure the current through the air between the plates as above, that is, measure the rate per second at which Q receives a charge as indicated by the number of scale divisions moved over per second. Increase the potential of P by a volt or two and again measure the current. Still further increase the potential and determine the current produced. Repeat this for gradually increasing voltages and it will be found that the current rises with each increment of voltage until finally a stage will be reached at which the current will no longer increase even with a large addition of voltage. In making these observations take at least two or three readings at each voltage and take the mean as the reading at that voltage. This is necessary on account

of the slight variations in the rays given out which cause variations in the current.

Plot this series of readings on a curve having for abscissæ the voltages applied to *P,* and for ordinates the corresponding currents observed in each case. Since the current is proportional to the number of scale divisions per second the latter may be plotted for the current. This curve showing the relation between the voltage and the current will assume the form shown in Fig. 32. It will be seen that for small voltages the current obeys Ohm's law, but soon begins to fall off and finally reaches a constant maximum value even for a large increase in voltage. This characteristic curve is usually called a *saturation curve* on account of its similarity in form to the saturation tion curve in the magnetization in iron. The current corresponding to the flat part of the curve is called the *saturation current.* When the current through a gas between two electrodes is spoken of the *saturation* current is meant unless it is specifically stated otherwise, and when a comparison of currents under any conditions is being made it is always the saturation current that is used unless otherwise definitely specified. It is extremely important to observe this or else serious confusion and error will arise. The voltage necessary to produce saturation in each particular instance should always be tested as the point of saturation will be reached for different voltages under different circumstances.

FIG. 32.

56. Variation of Current with Distance Between the Plates. —Replace the plate *P* (Fig. 31) by a sheet of wire gauze of the same size and turn *P* and *Q* through a right angle so that the rays fall perpendicularly upon *Q* after passing through the gauze *P* as shown in Fig. 33. Make exactly the same connections to the battery and electrometer as in Fig. 31. Make the potential between *P* and *Q* equal to about 300 volts. Place *P* and *Q* about 3 cm. apart and measure the saturation
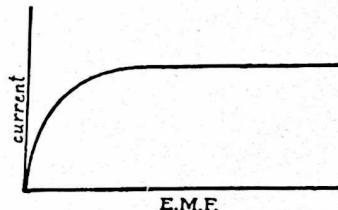
current. Increase the distance to 4 cm. and again measure the saturation current. Repeat this for gradually increasing distances until the current has been measured for six or eight different distances. Note that the current increases with the distance between the plates, although in each case it is the saturation current. If the plates are not too close together to start with the current in the different cases will be found to be practically proportional to the distance between the plates. This is quite different from the corresponding measurement of electric current through a solid or a liquid. When the distance between two plates immersed in a liquid is increased the current decreases on account of the increase of resistance between the plates. These experiments show however that just the opposite result takes place in the case of the current through air.
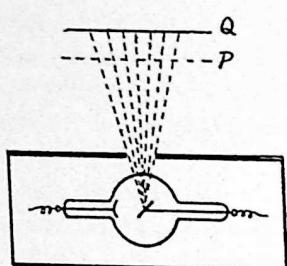
Fig. 33.

57. Theory of Ionization.—These phenomena along with others in connection with gases rendered conducting by the action of Röntgen rays led J. J. Thomson and E. Rutherford to formulate in 1896 the *ionization theory of gases* which now forms the basis of the whole subject of the conducting power of gases and which has become firmly established by experiment. According to this theory the Röntgen rays, when they pass through a gas, cause some of the molecules of the gas to be broken up into positively and negatively charged carriers of electricity called *ions*. The electromagnetic energy of the Röntgen rays causes a negatively charged electron to be separated from the molecule of the gas acted upon, leaving the remainder of the molecule positively charged. This process of separation is called *ionization*, and the gas is said to be ionized. From each molecule ionized two ions having equal charges but of opposite sign are thus produced.

This theory explains very satisfactorily the different properties of an ionized gas. The transference of electricity

through the gas is due to the movement of these charged carriers under the influence of an electric field. The positive ions are attracted towards the negative electrode and the negative ions to the positive electrode, and the movement of these electric charges constitutes a current. Since these ions are charged it is clear why the conductivity is removed when the gas is passed through the tube with the central wire between which there is an electric field, for the positive and negative ions are attracted to the negative and positive electrodes respectively and thus removed from the gas. When the gas containing ions is passed through cotton wool or through the water the ions are caught and left behind. The number of molecules which become ionized even in a strongly ionized gas is extremely small compared with the total number of molecules present, the number being probably of the order of only two or three in a million. Thus when the gas is passed through the electric field or wool filter there is little chance for many ions to escape being caught and removed.

The gradual disappearance of the conductivity of a gas follows naturally from this theory. When the ions are moving about in the gas if a positive and a negative ion come near enough they will attract each other and unite and thus neutralize each other. The ions thus recombine, and as far as their electrical effects are concerned disappear.

This theory explains the saturation curve showing the relation between voltage and current through a gas between two plates. The greater the potential difference between the plates the greater the force drawing the ions out of the gas and consequently the faster they will move towards the plates. The faster they move the greater will be the number that reach the plates per second, and besides by moving more quickly the less will be the chance of their recombining and therefore there will be more to reach the plates per second. The number of ions that reach the plates per second will therefore be proportional to the potential. The current is proportional to the charge given to the plates per second and therefore to the number of ions arriving at the plates each second. The cur-

rent is therefore proportional to the potential at the lower voltages. When however the voltage reaches a certain amount the ions move so fast that they practically all reach the plates before they have time to recombine. At such a voltage all the ions will be removed and the current therefore can not be increased further by increase of voltage. The current will therefore reach a maximum and remain so for any increase in the potential.

The explanation of the increase of current between two plates when the distance between them is increased is obvious from this theory. When the distance is increased the volume of gas acted upon by the rays is increased and consequently the number of ions produced grows larger in the same proportion. There are more ions between the plates and therefore a greater number will be drawn to the plates in unit time.

58. Absolute Measure of Current.—Instead of simply comparing the different currents through an ionized gas their value may easily be determined in absolute measure. If the gas is very strongly ionized the current may in a few cases be large enough to be measured by a very sensitive galvanometer. Under these circumstances replace the electrometer and condenser in Fig. 31 by the sensitive galvanometer, and, knowing the constants and calibration of the galvanometer, determine the saturation current in the same manner as you would measure the current in a metallic conductor. As a rule however the ionization current is too small to be measured by this method and the electrometer method must be used. It has been shown (§ 20) that if d be the number of scale divisions passed over per second by the electrometer needle as the insulated quadrants charge up to any given potential, and d_1 the number of divisions corresponding to a potential of one volt on these quadrants, and C the total capacity in microfarads of the system then the current $i = C/10^6 \times d/d_1$ amperes. Using the apparatus shown in Fig. 31 make a series of measurements of different currents in amperes as follows: Run the X ray bulb a few times for fifteen-second intervals with a rest of fifteen or twenty seconds between so as to get it running uni-

formly. Then start to take readings. Earth the plate Q and electrometer by the key K and see that the electrometer needle is at rest. Start the bulb and let it run for five seconds. At the end of the five seconds, without stopping the bulb, pull the cord which opens the key K, thus insulating the plate Q and allowing it to charge up. Let it charge up for, say, ten seconds, and at the end of this time shut off the bulb by opening the switch which controls the coil. When the needle comes to rest take the reading. Then earth the electrometer again to bring the needle to zero. Take the time carefully in these observations by means of a stop watch or accurate chronometer. The number of divisions d are thus obtained. Repeat this procedure in each case. Determine d_1 by means of the standard cell as described in § 17. Measure the capacity C of the system including the plate Q, the condenser C and the electrometer by one of the methods described in § 19. Supply these values obtained in the above equation and determine i in amperes. The following may be given as a typical example of such a determination. Suppose the number of scale divisions moved over in ten seconds is 150, which would be a convenient rate; therefore $d = 15$. Let $d_1 = 600$ scale divisions and let $C = .001$. Then i will be $.001/10^6 \times 15/600$ which equals 2.5×10^{-11} amperes. Currents considerably less than this may be measured with accuracy as a much slower rate than fifteen divisions per second may be observed with great ease.

59. Guard-ring Method.—In measuring the ionization current between two plates a still further and important precaution must be taken in the arrangement of the plates in order to secure greater accuracy. When a difference of potential is established between two parallel plates the electric field is not strictly perpendicular to the plane of the plates over the whole area of the plates, but only over the central portion, the lines of force, near the edges spreading out in curved lines. The above measurements are made on the assumption that the field is uniform, therefore only the portion of the ionized gas in the space between the central areas should be used.

This may be done by using what is called the guard-ring method. The central portion of the plate Q is cut out, leaving a margin 3 or 4 cm. in width. The part cut out is replaced by a plate A, Fig. 34, which is just a little smaller than the opening, so that there is a space all round of only about 0.5 mm. This central portion should be carefully insulated which may be done conveniently by supporting it by U-shaped pieces of ebonite fastened to itself and to the outer rim by screws. This central part A is then connected to the electrometer, while the outer rim is connected to earth. The plate P remains the same size as the outer rim. The ionization is thus measured only throughout the central part of the field over the area of A where the field is uniform. This principle of the guard-ring is applicable in a great variety of cases, and in all such cases as we have been considering where the uniformity of the field is necessary it should be used.
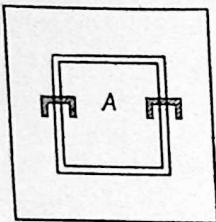
FIG. 34.

60. Dependence of Ionization on Quality of the Rays.—The number of ions produced in a given volume of air, and therefore the current through it, depends to a great extent upon the quality of the rays employed. " Soft " rays are more efficient ionizers than " hard " or penetrating rays. To secure a large amount of ionization in a gas it is best to use a moderately " soft " bulb. If several bulbs are available which give out rays of different qualities measure the ionization produced by each one in turn in the same space between the guard-ring plates and under the same conditions. If the automatic bulb of the type shown in Fig. 30 is available vary the quality of the rays by varying the length of the spark gap between the main cathode and the auxiliary cathode. With a short spark length the rays given out are softer than for a longer spark gap, as with a short spark length the pressure in the bulb is comparatively higher. Measure and compare the amount of ionization produced when different lengths of spark gap are used,

that is for different qualities of rays. Unless the rays are so soft that they are diminished too much in intensity by absorption the softer rays should be found to.produce more ionization than the very hard rays.

In each case immediately after measuring the ionization and before altering the spark gap place a sheet of brass or aluminium in the path of the rays between the bulb and the guard-ring plates and measure the ionization produced by the rays after passing through the plates. If the rays are very penetrating a great proportion of them will go through the plate and be effective as ionizers on the other side, but if they are not very penetrating a very small proportion will get through and therefore the ionizing effect will be cut down. The ratio in which the ionization is decreased by passing the rays through the metal sheet will be a measure in the inverse ratio of the penetrating power of the rays. By means of these measurements compare the relative penetrating power of the rays with their ionization power for rays of different qualities.

61. Absorption of Röntgen Rays. (*a*) *By Solids.*—Different materials absorb Röntgen rays of any given type by different amounts. An approximate qualitative comparison of the relative absorbing powers of bodies has been given in § 43. We are now in a position to measure these absorptive powers more definitely. Place the usual set of guard-ring plates about 18 or 20 cm. in front of the window in the usual position. Measure the saturation current between the plates, then place a sheet of the absorbing material to be tested of a given thickness in the path of the rays between the bulb and the plates and measure the saturation current again. A comparison of the currents in the two cases will give the percentage of the rays absorbed, as the decrease in the ionization will be proportional to the decrease in the quantity of rays due to absorption. Secure as large a variety as possible of sheets of different kinds of metal, glass, wood, etc., all of the same thickness of about 2 or 3 mm. Compare the absorption produced by the different materials and note carefully the great range of absorbing powers. Repeat this series, using a different quality of rays and note that

the relative penetrating powers may not necessarily be the same for different kinds of rays. Make a comparative table of these measurements for reference.

Now select any one material which may be obtained in thin sheets of uniform thickness, such as tinfoil or aluminium foil. Measure the absorption produced by a single sheet of tinfoil, then introduce another sheet and measure the absorption produced by the double thickness. Continue thus adding a sheet at a time and observe how the absorption increases with the thickness. It will be found that this absorption does not increase in direct proportion to the thickness. If a bulb of medium hardness is used it will be found that the first few layers of tinfoil produce a greater percentage effect than the remaining layers, owing to the fact that there is a mixture of rays of different penetrating powers and the softer rays are largely absorbed by a few thicknesses of metal, while the harder ones pass through with little absorption, and after the softer rays are cut out more layers in proportion have to be introduced to cut down the intensity of the more penetrating rays to the same amount. Measure the absorption produced by the different substances in this way. Repeat these measurements, using different qualities of rays.

(*b*) *Standard Test.*—In making a series of measurements such as the above, in order to obtain any reliable comparisons, the source of the rays must remain constant throughout, or if it does not there must be some means of checking any change in the source and correcting for it. For this reason a separate test apparatus should be introduced to detect and correct for any change if it does occur. A convenient arrangement for this purpose is. shown in Fig. 35. P and Q are the guard-ring plates corresponding to the plates P and Q in Fig. 31, the connections of which are the same as before. Another set of plates R and S exactly similar to P and Q, but only about one half or one third the size, are introduced in the position shown and form a standard test apparatus. S is connected to a separate condenser and to a key H of the form shown in Fig. 11 (*b*), so that S may be insulated from or connected to

the electrometer at will. If H is raised then S is insulated, and while the rays are acting it will charge up. If H is closed while K is open this charge is thrown into the electrometer and it may be measured. The test of the constancy of the rays should be made in the following manner: Run the bulb in the usual way and open the keys H and K at the same instant. S charges up for the same time as Q but is insulated from Q. Take the reading for Q and then discharge Q by earthing it
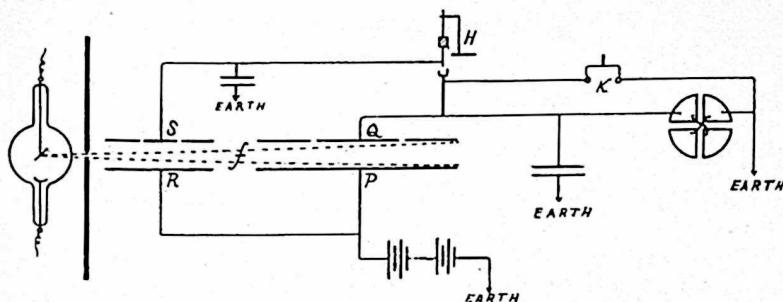
FIG. 35.

through K. When the needle comes to rest insulate Q again and then close H, thus throwing the charge contained by S and its condenser into the electrometer. Take the reading for this charge. This gives a measure of the ionizing power of the rays between S and R. For each measurement of current between P and Q make the simultaneous measurement between R and S. If any change in the rays occurs it will be detected by the standard RS, and a correction may be made for the readings for the current between P and Q. The absorbing body which is to be tested is placed in the space f between P and R. The introduction of these absorbing bodies thus does not affect the conditions between R and S, while it does between P and Q. If the test apparatus were absent one could not be certain whether any change in the ionization between P and Q were due entirely to the absorption of the body at f or partly due to this and partly due to a change in the source of the rays. In all measurements of this type this test apparatus should be used as a check on the rays.

7

(c) *By Liquids.*—Liquids also absorb Röntgen rays to a considerable extent. The absorption produced by liquids may be measured in exactly the same way as that produced by solids, by placing the liquid contained in a cell with parallel glass sides in the space *f* and testing as before. In this instance to obtain the absorption produced by the liquid alone the absorption produced by the cell when empty must be separately measured and subtracted from the total absorption produced by the cell plus the contained liquid. Compare in this way the absorption produced by various liquids. Also select any given solution and measure the absorption for different concentrations of the solution.

(d) *By Gases.*—Röntgen rays are absorbed by gases in their passage through them, but of course to a very much less extent than by solids or liquids. Suppose that I is the energy, or intensity, of the rays, and when they pass through unit length of the gas a fraction λI of the energy is absorbed, then a small change dI in the intensity in passing through a small distance dx is given by the relation $dI = -\lambda I dx$, since dI is a decrease while dx is an increase.

Therefore
$$\frac{dI}{I} = -\lambda dx;$$

Therefore by integration $\log I + c = -\lambda x$ where c is the constant of integration. Therefore if I_0 is the intensity of the rays when $x = 0$, that is the intensity before any absorption takes place,

$$\log I - \log I_0 = -\lambda x.$$

Therefore
$$\frac{I}{I_0} = \epsilon^{-\lambda x},$$

and
$$I = I_0 \epsilon^{-\lambda x}.$$

The fraction λ is usually termed the coefficient of absorption. It is a comparatively small number, and it is not so easy to measure by the same method as was used in the case of solids

and liquids as gases produce such a comparatively small amount of absorption. The following experimental method used by Rutherford and the author is a convenient one for determining λ and comparing the absorptive powers of gases under different conditions. The arrangement of the apparatus is shown in Fig. 36. A and A' are two brass tubes about 5 or 6 cm. in diameter and about one meter long. The ends are closed by aluminium caps about 1 mm. thick. These tubes should be made as nearly as possible exactly alike and should be gas-tight. They are placed symmetrically with regard to the bulb, so the central axis of each passes through the center of the anode of the bulb. CD and $C'D'$ are two exactly similar sets of guard-ring plates for determining current. C and D' are connected to opposite poles of the battery. D and C' are connected together and to the electrometer. The guard-
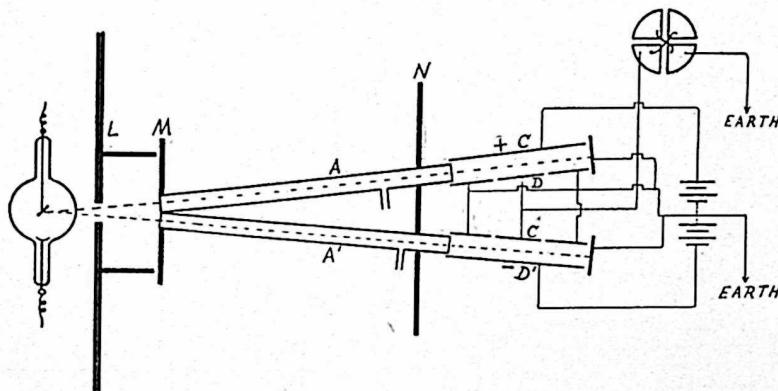
FIG. 36.

rings are, as usual, connected to earth. When the air between these two sets of plates is ionized the plates D and C' will receive charges of opposite sign, and if the amount of ionization is the same in both cases, the charges will be equal and the electrometer needle will show no deflection. M and N are thick lead screens to prevent any stray rays from reaching the test plates.

Place the several parts of the apparatus in position as sym-

metrically as possible; then test whether the electrometer needle balances under the influence of the two opposite ionization currents. If not, adjust the position of the two sets of plates by trial until a balance is obtained. The rays in passing through the tube are absorbed by the gas in the tube. If the air be exhausted from A the absorption in A will be lessened and the intensity of the rays which reach CD will be greater than the intensity of those which reach $C'D'$, and the balance will be destroyed. If both tubes are completely exhausted the balance should be restored.

Suppose that I is the intensity of the rays which reach either set of plates when both tubes are completely exhausted; then when both tubes are full of air at atmospheric pressure the intensity will be $I\epsilon^{-\lambda d}$, where λ is the coefficient of absorption and d the length of air passed through. Since the currents between C and D and between C' and D' are proportional to the intensity of radiation, therefore if A is exhausted and A' full of air the difference between the currents will be proportional to the difference between the intensities I and $I\epsilon^{-\lambda d}$, that is, to $I - I\epsilon^{-\lambda d}$. Suppose again that the rays coming through A' be completely cut off by a lead screen while A is still completely exhausted, then the current between C and D will be proportional to the intensity I when no absorption takes place, and therefore

$$\frac{\text{Diff. bet. currents when } A \text{ is exhausted and } A' \text{ full of air}}{\text{Total current when } A \text{ is exhausted and rays through } A \text{ cut off}}$$

$$= \frac{I - I\epsilon^{-\lambda d}}{I}.$$

Let $d_1 =$ rate of movement of the needle when A is exhausted and A' full of air,

Let $d_2 =$ rate of movement when the rays through A' are cut off by lead screen.

Then

$$\frac{I - I\epsilon^{-\lambda d}}{I} = \frac{d_1}{d_2}.$$

Therefore $\qquad\qquad$ $1 - \epsilon^{-\lambda d} = \dfrac{d_1}{d_2};$

then by expansion $\qquad$ $\lambda d = \dfrac{d_1}{d_2},$

since λ is very small and terms beyond the first power may be neglected.

Start with both tubes full of air and adjust till a balance is obtained. Exhaust A and observe the deflection d_1. Then place a thick lead screen between A' and the plates $C'D'$ and observe the deflection d_2. Measure the length d of the tube and calculate λ.

No constant standard value can be given for this coefficient, for it varies with the quality of the rays. The softer the rays the larger will be the value of λ. Rutherford and the author, working with fairly penetrating rays, obtained a value equal to 0.000279, but the coefficient may be much larger with softer rays.

Measure the coefficients of absorption for any other gases which may be conveniently obtained. Compare also the absorbing powers of different gases by first filling both tubes with air at atmospheric pressure and balancing and then replacing the air in A by other gases in turn and observing the alteration in balance in each case.

62. Dependence of Ionization on Pressure of the Gas.—For a given type of rays the amount of ionization depends upon the pressure of the gas. The number of molecules in a given volume is proportional to the pressure of the gas and consequently the number of molecules to be ionized increases with the pressure and an increase in ionization with increase of pressure is to be expected. To measure this experimentally an air-tight ionization chamber will be necessary. A suitable one is shown in Fig. 37. AB is a brass cylinder about 15 cm. diameter and 30 cm. long, the walls being about 2 mm. thick. The end B is closed by a brass plate soldered or brazed to the cylinder. At the other end a heavy brass flange cd about 0.5

cm. thick and 3 cm. in width, fitting the cylinder tightly, is soldered to it. An aluminium plate about 0.5 cm. thick and of the same diameter as the flange is made to fit closely on the face of the flange, so it may be bolted firmly to it. These surfaces should be turned as smooth as possible to obtain a close fit. The central part of this plate is recessed down to a thick-
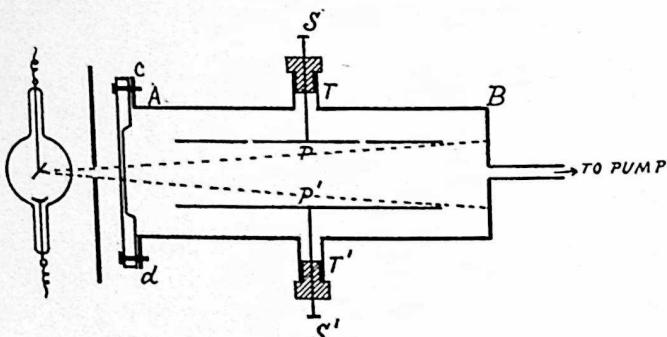
FIG. 37.

ness of about 1 mm. over an area of 6 or 8 cm. in diameter so as to allow the rays to pass into the cylinder without being diminished too much in intensity in passing through the aluminium. The joint between the plate and the flange may be made air-tight by placing a soft lead wire about 1 mm. in diameter in a circle on the flange inside the bolts and then placing the aluminium plate on the wire and bolting it down tightly until the wire is squeezed down to about half its original thickness, as described in § 31. T and T' are two side tubes 5 cm. long and placed diametrically opposite. P and P' are a set of guard-ring plates about 6 cm. apart made of aluminium. S and S' are two stout brass rods which pass through ebonite plugs in the ends of the tubes T and T' and support the plates P and P'. These rods should fit tightly in the ebonite plugs and may be made to screw into the face of the plates P and P'. The ebonite plugs and the inside of the tubes T and T' should be threaded so that the plugs may screw into the tubes to withstand the strain when the gas pressure is increased from within. If all these joints are carefully made to fit tightly they can

finally be made perfectly air-tight by waxing with paraffin. The plates P and P' are connected in the usual way through S and S' to the electrometer and battery respectively.

Place this apparatus a short distance in front of the Röntgen ray bulb and very carefully adjust the position of the cylinder and the size of the cone of rays so that the rays will pass between the plates without touching them. This adjustment is very important, in order to avoid any secondary radiation at the surface of the plates, and it may be very accurately made by calculating the distances and dimensions for the cone of rays and leaving a sufficient margin for safety. Place the standard test apparatus between the bulb and the cylinder so as to test the constancy of the rays during the experiment.

Starting with the air at atmospheric pressure measure the saturation current between the plates. Then reduce the pressure by about 10 cm. by the air pump and measure the saturation current and also measure the pressure of the air. Repeat this until the pressure is reduced to a centimeter or less. Also increase the pressure by stages above atmospheric pressure by pumping air into the cylinder, and measure the saturation current at the different pressures until a pressure of two or three atmospheres is reached. At each measurement test the intensity of the rays by the standard test apparatus and if any change occurs correct for it. More than one reading should be taken at each pressure and the mean taken to ensure greater accuracy. Plot a curve showing the relation between ionization and pressure. This curve should be a straight line showing that the ionization is proportional to the pressure.

63. Dependence of Ionization on the Nature of the Gas.— Another important factor on which the ionization depends is the nature of the gas ionized. For any given type of rays the amount of ionization produced in a given volume of gas under constant conditions is quite different for the different gases. The heavier gases, as we have seen, absorb the rays more than do the lighter gases, and the greater the absorption the greater the ionization. The ionization produced in different gases may be measured by means of the apparatus used in the last experi-

ment (Fig. 37). Starting with air at atmospheric pressure measure the saturation current. Then exhaust the cylinder as rapidly as possible and refill with another gas, say hydrogen, and measure the current. Repeat this for all the different gases which may be conveniently used, avoiding, of course, any gases which will act upon the metals in the vessel. The relative ionization in the different gases will thus be obtained by reducing these readings to the same scale.

In replacing one gas by another it is best to exhaust and refill two or three times, so as to ensure that no trace of the preceding gas remains. Make sure also that the pressure is the same in all cases. Keep the temperature as nearly constant as possible. In filling the cylinder with gas dry the gas very thoroughly by passing it through a series of drying agents as it passes into the cylinder. If this precaution is neglected serious trouble will result due to the destruction of the insulation inside the cylinder, as well as the complication of results by the different amounts of moisture present at different times. As usual test the rays at each reading by the standard test apparatus.

Use a different quality of Röntgen rays either by using another bulb giving out a different type of rays or by altering the spark gap in the self-regulating bulb and repeat the experiments with the same set of gases. If the rays used in the two sets of readings differ considerably in quality it will be found that the set of numbers showing the relative ionization in the second case will differ somewhat from those obtained in the first instance.

These experiments show that in general the denser the gas the greater the amount of ionization produced by Röntgen rays. The relative ionization is not however proportional to the relative densities of the gases. The relative ionization depends upon the quality of the rays used. The more penetrating the rays the more nearly does the ionization become proportional to the density of the gases, but no rays have as yet been found to give exact proportionality.

64. Recombination of Ions. (a) Theory.—We have seen

(§ 47) that the conductivity imparted to a gas by Röntgen rays persists for a short time after the rays have ceased. The conductivity gradually disappears, and the greater the quantity of ionization the more rapid will be the rate at which it dies away. If a comparatively weak source of rays be used it is found that when the rays begin to ionize the gas the saturation current gradually increases, showing that the ions gradually increase in number until a steady state is reached, when no further increase in the number will take place, no matter how long the rays act. As the rays are continually producing ions they must be disappearing at the same rate as they are being produced when the steady condition is reached. What becomes of them? They are positively and negatively charged bodies and in moving about in the gas must collide with one another. When a positive and negative ion come together they neutralize each other electrically and disappear, as far as producing any conductivity is concerned. The rate at which this recombination of the ions takes place is an important factor in determining the current through a gas. When the number of ions is large the chances of collision are increased and the rate of recombination is consequently greater than when the number of ions is small.

The positive and negative ions per cubic centimeter are equal in number. Suppose the number of each is n. Then the chances of collision taking place will be proportional to $n \times n$. Therefore the rate at which they recombine will be proportional to n^2 and will consequently equal αn^2, where α is a constant independent of n. This constant α is called the coefficient of recombination and is the fraction of collisions which result in recombination. Suppose that q is the number of either positive or negative ions produced per second per c.c. at any stage of the ionization. Then the rate of change in the number of ions must equal $q - \alpha n^2$. But the rate at which the ions change is equal to dn/dt, where dn is the small change in number in the time dt. Therefore,

$$\frac{dn}{dt} = q - \alpha n^2. \qquad (1)$$

If the rays be suddenly cut off then q becomes zero and

$$\frac{dn}{dt} = - an^2,$$

therefore

$$\frac{dn}{n^2} = - a\,dt.$$

Therefore by integration $- 1/n = - at + c$ where c is a constant and n is the number of ions per c.c. at a time t after the rays cease. Let $N =$ the maximum number of ions per c.c. at the instant the rays cease, that is when $t = 0$.

Therefore

$$\frac{1}{n} - \frac{1}{N} = at. \tag{2}$$

This equation gives the number of ions n per c.c. at any time t after the ionizing source has ceased to act if a and N are known.

Again suppose that before the rays cease a steady state exists, that is, the rate of production is equal to the rate of recombination. Under these conditions no change is taking place in the number of ions present per c.c., and consequently $dn/dt = 0$, and therefore, by equation (1), $q = aN^2$, since in the steady state $n =$ the maximum number N.

Therefore

$$a = \frac{q}{N^2}. \tag{3}$$

If the ions are produced within a given volume of gas between two electrodes such as two parallel plates, and since q is the number produced per second per c.c., then the quantity of electricity produced per c.c. per second will equal $q \times e$ where e is the charge on each ion. Therefore if the saturation current c between the plates be measured in absolute measure $q \times e$ will be proportional to this current and therefore $q \times e = kc$ where k is a constant.

Again if the ionization be allowed to reach the steady state

with no difference of potential acting between the plates, then N will be the number of ions actually existing per c.c. at any instant during that steady state, and therefore $N \times e$ will be proportional to the total quantity of electricity existing in the given volume of gas. If the rays be suddenly stopped and at exactly the same instant a high potential be established between the plates so that all the ions are suddenly driven to the plates before any recombination can take place then $N \times e$ will be proportional to the whole charge c_1, measured in absolute units, received by the plate. Therefore $N \times e = k_1 c_1$, where k_1 is a constant. Therefore supplying these values for q and N in equation (3) α will equal

$$\frac{\dfrac{kc}{e}}{\left(\dfrac{k_1 c_1}{e}\right)^2}.$$

Therefore $\qquad \alpha = \dfrac{k}{k_1^2} \cdot \dfrac{c}{c_1^2} \cdot e\,;$

$$= K \cdot \frac{c}{c_1^2} \cdot e \quad \text{where } K = \frac{k}{k_1^2}.$$

This constant K depends upon the dimensions of the apparatus and its position relative to the Röntgen ray bulb. By measuring c and c_1 and determining K for the particular apparatus the value of α may be determined in terms of e, the charge on an ion.

(b) *Experimental Determination.*—The actual experimental determination of α is somewhat troublesome, presenting several difficulties, and extreme care must be taken to secure satisfactory results. It has been measured in absolute measure independently by Townsend, Langevin and the author, each one using a different method, the author using the one described above. The values obtained by these for α in air at ordinary pressure and temperature were respectively $3420 \times e$, $3200 \times e$ and $3384 \times e$, where e is charge carried by an ion.

The following experiment will show in a fairly simple manner the rate at which the ions recombine and may be used to verify the formula in equation (2). AB (Fig. 38) is a brass tube about 4 cm. in diameter and about a meter long.
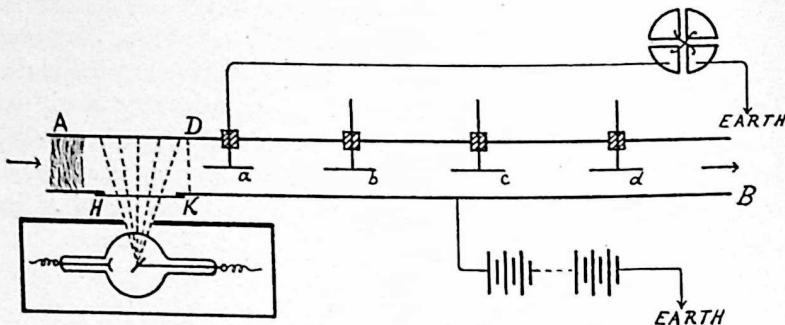
Small brass rods a, b, c and d, all exactly alike and about 6 or 8 cm. long, are held in place on the axis of the tube by brass rods passing through ebonite plugs in the side of the tube. At HK about half the tube is cut away for a length of 10 cm. and the opening is covered with thin aluminium. This is to allow the rays to pass into the tube and ionize the gas in the part AD. Pass a slow steady current of air through AB from a gasometer by weighting the gasometer so as to secure constant pressure. Maintain this stream of air as steady as possible. Place a plug of glass wool at A so as to remove all dust particles from the air as it enters AB. . As the air passes AD it is ionized and this ionized air is carried past the electrodes a, b, c and d. The farther the air proceeds along the tube after passing D the longer time have the ions to recombine, and the number of ions at each electrode should be less than at the preceding one. Connect the outer tube to the battery as shown and connect the electrode a to the electrometer and measure the saturation current. Then connect b to the electrometer and measure the current, and do this in turn for each of the electrodes. In each case all the electrodes but the one connected to the electrometer must be connected to the

tube so there is no field between the tube and these electrodes to extract the ions before they reach the particular one under consideration. The current should be proportional to the number of ions per c.c. in the gas as it passes each electrode. The decrease in this current as we pass from one electrode to the next is a measure of the decrease in the number of ions in the time taken for the air to pass from one electrode to the next. This time taken by the air to pass between two electrodes may be determined by observing the total volume of air which leaves the gasometer per second and measuring the cross-section of the tube *AB*. By altering the speed and repeating the measurements the conductivity corresponding to other intervals of time may be obtained. Knowing the exact position of the volume of air ionized by the rays determine the time taken by the air to pass from this position to each electrode in turn. Let these times be t_1, t_2, etc., and let the number of ions per c.c. at each electrode be n_1, n_2, etc., which are proportional to the conductivity measured at each electrode. Plot a curve having as ordinates the conductivities and as abscissæ the corresponding times.

In equation (2) the value of n for any given time t may be obtained if N and α are known. Supply two of the experimental values for n_1 and n_2 along with the corresponding values for t_1 and t_2 in the equation and thus obtain two numerical equations in N and α, and from these solve for N and α in relative numbers. Now supply these numerical values for N and α in equation (2) and a general numerical equation between n and t will be obtained. Select any values for t and solve for the corresponding values for n and then plot these theoretical values for n and t on the same scale as the experimental curve already plotted and compare these two curves. The experimental curve and the theoretical one should agree very closely, thus verifying the theoretical curve and the formula from which it was obtained.

65. Diffusion of Ions. (*a*) *Theory.*—If two gases, such as hydrogen and carbon dioxide for instance, are brought together and left in contact and undisturbed they gradually intermingle

or diffuse into one another owing to the motion of the molecules. The same thing occurs in the case of an ionized gas. The ions are in motion, and if there is an excess of ions in one part of the gas they will diffuse to the other part. If the ionized gas is in a closed vessel or between plate electrodes the ions will diffuse to the sides of the vessel or the plates and disappear from the gas. Sometimes in a very confined space the diffusion to the walls or electrodes is an even more important factor than recombination in causing the loss of ions, but in a large volume of gas the diffusion is much less important in comparison with recombination. A study of this diffusion of ions throws considerable light on the conditions existing in an ionized gas and leads to some important results.

The rate at which the ions diffuse depends upon the nature of the gas in which they exist, as is to be expected, just as the rates at which different gases diffuse are different. The diffusion of ions through the heavy gases is slower than through the lighter ones. In a very dry gas the negative ions always diffuse faster than the positive ions, while if the gas contains considerable moisture the rates of diffusion of the positive and negative ions are much more nearly equal. The rates of diffusion of the positive and negative ions differ more in some gases than in others. This difference between the positive and negative ions explains the phenomenon which is so often observed that if an ionized gas containing equal numbers of positive and negative ions be passed through a metal tube it will emerge positively charged. The negative ions diffuse faster to the sides of the tube than do the positive ions, and consequently more negative than positive ions are lost and the gas emerges with an excess of positive electricity.

The rate at which ions diffuse through gases is much slower than the rate of interdiffusion of ordinary gases. For instance, air and carbon dioxide interdiffuse over five times as fast as the positive ion diffuses through moist carbon dioxide. Heavy gases diffuse slower than light ones, and since the rate of diffusion of both the positive and negative ions in carbon dioxide is so small compared with the rate of diffusion of

carbon dioxide into air, the natural conclusion is that the mass of the ion in carbon dioxide is large compared with the mass of the molecule. This is true in the case of other gases also.

These facts have led to the theory that both the positive and negative ions at ordinary pressures consist of a cluster of molecules surrounding a charged nucleus. Ionization is believed to consist in the separation of a negative electron from the neutral molecule and then this charged electron becomes loaded with a cluster of molecules of gas and forms the negative ion under ordinary conditions. The positive ion, on the other hand, consists to begin with of the molecule deprived of the electron and then a cluster of molecules forms about this positively charged centre. This theory accounts for the fact that the positive and negative ions diffuse more nearly at the same rate in moist than in dry gases, for in dry gases the negative ion is smaller, but in moist gases it becomes more loaded up with moisture than does the positive ion, and consequently its rate of diffusion decreases more than that of the positive ion.

This theory is supported by the fact that as the pressure of the gas is lowered the coefficient of diffusion of the negative ion increases faster than that of the positive. It has been shown by J. J. Thomson and by Townsend that at low pressures the negative ion is identical with the electron. These facts point to the conclusion that the negative ion at low pressures loses the cluster of molecules attached to the electron.

The calculation of the rate of diffusion in most cases becomes somewhat complicated, but as an illustration one of the simplest cases will be considered here namely the diffusion of the ions between two parallel plates. Let P and Q (Fig. 39) be two parallel plates in the ionized gas and consider the

FIG. 39.

passage of the ions by diffusion across a small rectangular space of thickness dx and cross section $ABCD$ of unit area.
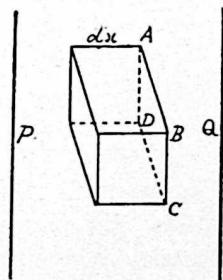
Let n be the number of positive and m the number of negative ions per c.c. Then the number of positive ions that pass across the face $ABCD$ per second by diffusion will be proportional to dn/dx and will be equal to $D\ dn/dx$, where D is a constant. Therefore the rate of increase of the positive ions in the small volume will be d/dx of ($D\ dn/dx$) which equals $D\ d^2n/dx^2$. If q is the number of ions per c.c. produced in the gas per second by the ionizing source then the total rate of change in the number of ions per second which is dn/dt will be made up of three factors, namely, rate of production q, rate of diffusion $D\ d^2n/dx^2$, and rate of recombination anm.

Therefore

$$\frac{dn}{dt} = q + D\frac{d^2n}{dx^2} - anm,$$

since q and $D\ d^2n/dx^2$ both tend to increase the number in the small volume while anm tends to decrease the number. When a steady state is reached $dn/dt = 0$, since there is no change, and therefore

$$q + D\frac{d^2n}{dx^2} - anm = 0.$$

If the plates are very close together so that the loss in the number of ions due to diffusion is much more marked in comparison with that due to recombination, then the term anm may be neglected and the equation becomes

$$q + D\frac{d^2n}{dx^2} = 0.$$

If however the plates are several centimeters apart so that the loss by diffusion to the plates is very small compared with the loss by recombination, then the term $D\ d^2n/dx^2$ drops out and the equation reduces to the one we considered in connection with recombination alone. The quantity D is called the coefficient of diffusion and is one of the important constants in connection with ionization.

(b) *Experimental Determination.* — The experimental determination of this coefficient D in absolute measure involves some difficulties and requires very careful manipulation. The following comparatively simple experiment will serve simply to illustrate the rate of diffusion of ions without determining D in absolute measure. AB (Fig. 40) is a brass tube about 50 cm. long and 4 cm. diameter. CD is an aluminium window about 10 cm. long to allow the rays to enter the tube. Obtain some brass tubing about 3 mm. internal diameter and of as uniform bore as possible. Cut a dozen lengths exactly 10 cm. long. In two brass disks which tightly fit inside the large tube AB bore a dozen holes symmetrically arranged around the centre of the disks, and into these holes solder the small tubes as shown at ab. Make also another set
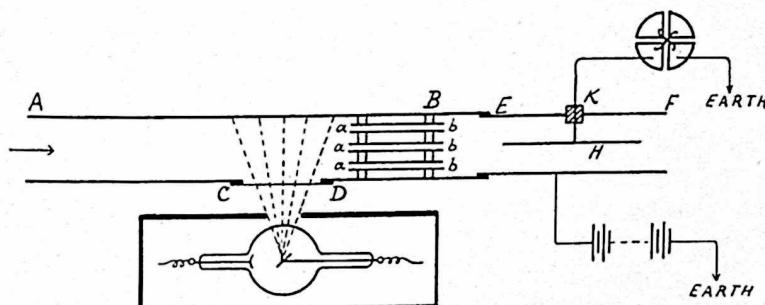
Fig. 40.

of a dozen small tubes exactly the same as above, only make them 1 cm. long instead of 10 cm. Make the disks to fit the tube AB accurately, so that no gas can pass between the disk and the larger tube, but not rigidly fastened so they may be removed. EF is a brass tube about 20 cm. long and just large enough to fit tightly into the end of AB, so that it may be removed at will. H is a central electrode about 10 cm. long, insulated by an ebonite plug K as shown. The tube EF and the electrode H are connected up in the usual manner for measurement as indicated.

Place the long set of small tubes at B and pass a steady

8

stream of air from a constant pressure gasometer through the system entering at A. The gas is ionized by the rays before it enters the small tubes and on its passage through them loses some of its ions by diffusion to the walls of these tubes. Charge the tube EF positively and the positive ions which escape from the tubes ab will be driven to the electrode H, and the rate at which H charges up will be proportional to this number of positive ions. Measure this rate of charge by the electrometer. Then charge EF negatively, and similarly the charge per second acquired by H will be proportional to the number of negative ions which escape from the tubes ab. Repeat these measurements several times, keeping the stream of air constant. Note that more positive ions escape than negative ions. Now replace this set of tubes by the set of short ones and repeat the measurements, being careful to maintain the stream of air of exactly the same velocity as before. In the second case more of both positive and negative ions should escape, as they have a shorter time to diffuse while passing through the tubes. Both sets of experiments should be repeated, using a stream of air of a different velocity. If the velocity is slower fewer ions should escape, while with greater velocity more should escape to be driven to the electrode H.

The air before passing into AB should be thoroughly dried and freed from dust particles by passing it through drying agents and through a plug of glass wool. These experiments may be repeated, using moist air, when it should be found that the difference between the diffusion of the positive and negative ions is less than in the dry air.

66. **Mobility of Ions.**—When an electric field is applied to an ionized gas the charged ions move under the influence of this field. The velocity with which they move is of importance in many cases. The velocity of the ions under a potential gradient of one volt per centimeter is generally termed the mobility of the ions. As in the case of diffusion the velocities of the positive and negative ions are not the same. The velocity of the positive ion in any given gas is always less than that of the negative ion.

The mobility of ions depends upon the nature of the gas in which they are produced, being greater in light than in heavy gases. In dry air, for instance, the velocities of the positive and negative ions respectively are 1.36 and 1.87 cm. per second for a potential gradient of 1 volt per centimeter, while in hydrogen the corresponding values are 6.70 and 7.95 cm. per second.

The presence of moisture has a marked effect on the mobility of ions, causing, as a rule, a diminution of velocity, especially in the case of the negative ion. This is more marked in some gases than in others. This diminution of velocity in the presence of moisture is a further indication, especially in the case of the negative ion, of an increase in size by becoming loaded with moisture.

The velocity of the ions also varies with the pressure of the gas, as would be expected, for the fewer the number of molecules present the less would the ions be retarded by collisions with the molecules, and they would thus have greater opportunity to gain in speed under the same electric field. This velocity is found to be very approximately inversely proportional to the pressure of the gas. At low pressures however an unusual increase in velocity of the negative ion takes place, greater than would be expected from the mere change in pressure, which indicates a diminution in size of the ion at the low pressure caused by the ion shedding the molecules which adhere to it.

There are several experimental methods which have been used to measure the velocity of ions under different conditions. Some of these are applicable only to a determination of the sum of the velocities of the positive and negative ions, while others are only suitable for special cases. By the following method, which is due to Zeleny,

.FIG. 41.

the velocity of either the positive or negative ions may be measured independently and under different conditions. The
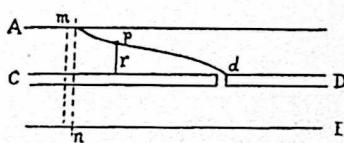
theory of the method is as follows: Suppose AB and CD
(Fig. 41) represent two coaxial metal cylinders between which
a stream of air is passed at a constant velocity in a direction
parallel to the axis. A narrow, well-defined section mn of
the gas as it passes along is ionized by Röntgen rays. A
constant difference of potential is maintained between the outer
and inner cylinders. The ions will therefore have two com-
ponent velocities, one due to the motion of the gas parallel to
the axis of the tube and the other at right angles to the axis
due to the electric field. If the outer cylinder be positive with
regard to the inner, then the path of a positive ion starting
from a point m will be represented by the line md. If the
potential be reversed this will represent the path of a negative
ion.

Let a and b be the radii of the inner and outer cylinders
respectively, E the potential difference between them and X
the electric field along the radius at any point p at a distance
r from the axis. Then by the ordinary formula for the electric
field between two coaxial cylinders,

$$X = \frac{E}{r \log_e \frac{b}{a}}.$$

Let v be the velocity of the ion due to unit electric field
and v_1 its velocity due to the field X. Then

$$v_1 = Xv = \frac{Ev}{r \log_e \frac{b}{a}}.$$

Let v_2 be the velocity of the air current parallel to the axis
and dx the small distance passed over in this direction in the
time dt; let dr be the distance traversed by the ion along the
radius at right angles to the axis in the same time. Then,
since the distance traversed is proportional to the velocity,

$$\frac{dx}{dr} = \frac{v_2}{v_1}.$$

Therefore $\qquad dx = \dfrac{1}{v_1} v_2 dr = \dfrac{r \log_e \dfrac{b}{a}}{Ev} v_2 dr\,;$

and $\qquad x = \dfrac{\log_e \dfrac{b}{a}}{Ev} \displaystyle\int v_2 r dr\,;$

where x is the total horizontal distance between mn and d.

Since the gas is travelling with a velocity v_2 cm. per second the volume of gas passing between the cylinders per second is equal to $\displaystyle\int_a^b 2\pi r v_2 dr$, which may be denoted by W, and therefore

$$\int_a^b r v_2 dr = \frac{W}{2\pi}.$$

Therefore $\qquad x = \dfrac{\log_e \dfrac{b}{a}}{Ev} \cdot \dfrac{W}{2\pi}\,;$

and $\qquad v = \dfrac{W}{2\pi Ex} \cdot \log_e \dfrac{b}{a}.$ $\qquad$ (1)

The volume W may be determined by observing the number of cubic centimeters of gas which leave the gasometer per second. The distance x is the maximum horizontal distance traversed by an ion starting from the inside surface of the outer cylinder and this distance depends upon the potential E; the smaller the value of E the farther will the ion travel in a horizontal direction. An ion which starts from a point nearer the axis than the inside surface of AB will not have a chance to travel so far, as it will be pulled in to CD sooner, and therefore only the ions which start from the inner surface will reach the distance x. To determine x experimentally the inner cylinder is divided at d by a narrow space so that the two parts are insulated, the right-hand one being connected to an electrometer and the left-hand part to earth. If E is great enough all the ions

will be pulled into the part Cd, but if E is gradually diminished a point will be reached when the ions just reach the part dD, and this is indicated by the movement of the electrometer needle. Thus the distance x is known and the corresponding value of E may be determined and W, a and b may all be
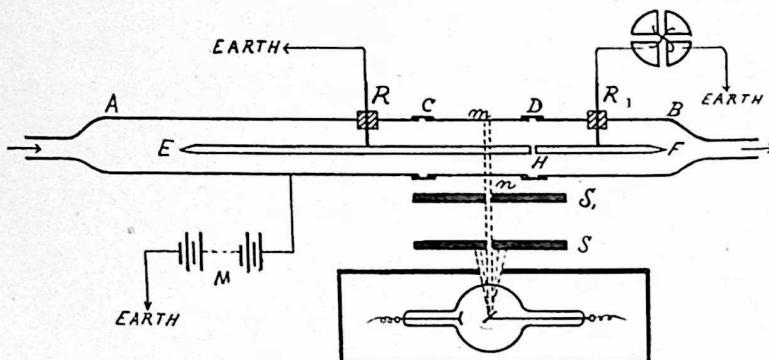

FIG. 42.

measured and the value of v calculated from equation (1).

In practice some small corrections have to be made on account of the diffusion of the ions and their mutual repulsions, etc., the details of which may be found in the original papers. The arrangement of the apparatus for this determination is shown in Fig. 42. AC and DB are brass tubes of the same diameter of about 5 or 6 cm. The part CD is a thin-walled aluminium tube of exactly the same internal diameter as the brass tubes. This is to allow the rays to pass through. These are fitted end to end and the joints made gas-tight by fitting a ring tightly around the joints and waxing them on the outside. The total length of these combined tubes should be about a meter. EF is a thin aluminium tube 1 cm. in diameter, coaxial with AB and closed by conical shaped ends and divided at the point H into two parts, so that the space separating them is 0.5 mm. These two separate portions are supported by two stout brass rods, R and R_1, passing through ebonite plugs fitting into the wall of the tube AB. At a distance of 4 or 5 cm. from

H a narrow cross section of the air is ionized by the rays from the bulb. The width of this section is regulated by two thick parallel lead screens, S and S_1, in which narrow slits are cut about 2 or 3 mm. in width. The electrode R_1 is connected to the electrometer, while R is connected to earth and the outer tube is connected to one pole of a battery, while the other pole is to earth. The steady stream of gas from the gasometer enters the tube at A. Start the stream of gas through the tube at a slow rate of only a few centimeters per second. Start the Röntgen ray bulb and put on a fairly large positive potential E on the outer tube from the battery M. Test whether the electrometer receives any charge. If it does increase the potential on AB till it receives no charge. Then, keeping the stream of gas perfectly constant, carefully adjust this potential until the electrometer is just on the point of receiving a charge. Observe this potential E_1 which will be the required value of E for the positive ion. Now reverse the battery and make AB negative and again carefully adjust the potential and let it be E_2. Then

$$\frac{\text{velocity of positive ion}}{\text{velocity of negative ion}} = \frac{E_2}{E_1}.$$

Find from this the ratio of the velocities of the positive and negative ions. Determine W from the gasometer and measure x, a and b and calculate from equation (1) the absolute velocity for both the positive and negative ions.

Change the speed of the air current and repeat the experiments, and from these observations determine the velocities. This should be done for several different speeds of air currents. These observations should give very approximately correct values without applying the various corrections mentioned above and will give a very good idea of the velocities of ions without making the experiment too elaborate.

In these experiments the air should be thoroughly dried before entering the tube by passing it through drying agents. Afterwards moist air may be used to test the effect of moisture

on the velocities. The velocities in different gases should also be determined if a sufficient supply of other gases is obtainable.

67. Ionization by Collision.—In a former paragraph (§ 55) the relation between the ionization current and potential in a gas at atmospheric pressure was considered, and there it was shown that when the voltage reached a certain value all the ions present were swept to the electrodes and no further increase of current could take place for an increase of voltage, and the saturation current was obtained. At low pressures however in the neighborhood of 1 mm. of mercury the relation between current and potential presents a new phenomenon which does not appear at the higher pressures.

This may be studied by means of the ionization chamber shown in Fig. 37. Adjust the distance between the plates P and P' to about 2 cm. Adjust the width of the cone of rays so that they do not touch the plates as they pass through the gas. Exhaust the vessel to a pressure of about 1 mm. Connect S and S' to the electrometer and to the negative pole of a battery respectively in the usual way. Apply a potential of only a few volts to S' and measure the current between the plates when the rays are acting. Increase the potential by a few volts and measure the current. Continue this until a potential of about 300 volts is reached, keeping the pressure constant. Plot the curve for current and voltage. Repeat this for two or three different pressures below a millimeter and plot the curves. The curves obtained should present the general form shown in Fig. 43. It will be observed that for comparatively low voltages the first part of the curve up to a point A is of the same form as the saturation curve at atmospheric pressure, but when the voltage
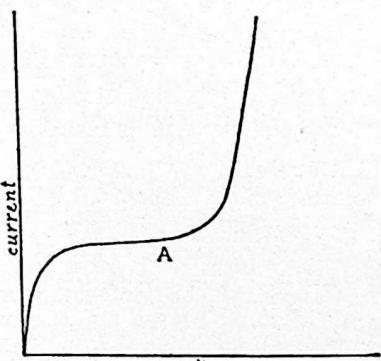
FIG. 43.

is increased beyond a certain amount the current begins to increase again, at first slowly and then very rapidly. The voltage at which this increase begins will depend upon the pressure of the gas. The increase of the current beyond the point *A* must be caused by an increase in the number of ions due to some cause other than the original ionizing source, for we have already seen that Röntgen rays produce fewer ions at low pressures than at high pressures.

Now we know that if a stream of rapidly moving cathode ray particles or electrons be allowed to pass between two electrodes in a cathode ray tube an ionization current is produced between the electrodes, showing that the rapidly moving electrons or ions must have ionized the molecules of the gas. To ionize a molecule a certain definite amount of energy is required. A moving ion possesses kinetic energy, and if the velocity is sufficiently great it will possess sufficient energy to ionize a molecule if it collides with it. Thus, if the moving ions acquire sufficient energy fresh ions will be produced. The kinetic energy of the ion depends upon the velocity and the velocity depends upon the electric field and upon the chance the ion has of acquiring speed among the molecules of the gas. At atmospheric pressure the molecules are so numerous that the ion is not able between two collisions to acquire sufficient velocity under ordinary electric fields to ionize the molecules by collision with them, but at low pressures the molecules are so few in number and far apart that the speed of the ion has a chance to increase sufficiently under smaller fields between collisions to ionize the molecules when it strikes them. Under these circumstances then the few ions produced by the Röntgen rays acquire sufficient velocity under the influence of the electric field to produce fresh ions by collision with the molecules and these ions in time produce more and the number increases very rapidly with the increase of voltage. This increase is therefore only observed at the lower pressures under ordinary conditions, for at the higher pressures the voltage necessary to produce the required velocity is so very large, being at atmospheric pressure about 30,000 volts. For ordinary electric fields

this production of ions by collision is only observed for pressures below about 30 mm. of mercury.

This theory of ionization by collision furnishes a very satisfactory explanation of the electric spark through a gas at atmospheric pressure. There are always a few ions existing in gases which can be detected only by sensitive instruments. If a voltage high enough to produce a spark is established between two points the few ions existing in the field will acquire a velocity sufficient to ionize the molecules against which they strike; these new ions in turn will produce more ions by collision, and so the number increases very rapidly, until there are enough ions to carry a current and this current is the electric spark. Since the gas is at atmospheric pressure the voltage required is very large, but with decrease of pressure the ions acquire velocity more easily and the potential necessary to produce the discharge decreases.

CHAPTER VI.

OTHER SOURCES OF IONIZATION.

68. Ultra-violet Light.—Up to the present we have, for the sake of simplicity, confined our attention chiefly to the ionization produced by Röntgen rays. Cathode, Lenard and Canal rays all produce ions, but these rays are limited in their application to gases at low pressure. There are still other sources from which ions may be produced. If ultra-violet light rays fall upon the clean surface of an insulated plate of zinc which is negatively charged the plate will lose its charge, while if the plate be uncharged to begin with it will acquire a positive charge. If the plate is positively charged to begin with, no loss of charge takes place. These effects, which are called photo-electric effects, have been shown to be due to the liberation of negative corpuscles, or electrons, from the metal by the action of the ultra-violet light. In a gas at atmospheric pressure the electrons become attached to the molecules and act as ordinary negative ions produced by other agencies, but if produced in a gas at very low pressure they do not become loaded with the molecules of the gas and consequently have a small mass.

69. Method of Producing Ultra-violet Light.—Light rich in ultra-violet rays may for general uses be obtained from various sources, such as an ordinary arc-lamp or the spark from an induction coil between zinc, cadmium or iron terminals. For making definite measurements however a constant source is desirable, and the following method will be found to produce very satisfactory results. Two iron wires *a* and *b* (Fig. 44) about 1 or 1.5 mm. in diameter are fitted into screws which are supported by a wooden frame
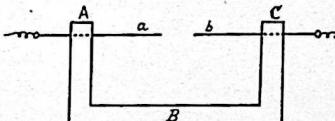

FIG. 44.

ABC. By means of these screws the distance apart of the ends of the wires may be adjusted. These wires are made the terminals of the secondary of an induction coil in parallel with which there should be a capacity of three or four good sized Leyden jars. An alternating current is sent through the primary and this current should be adjusted so that with a spark length of from 4 to 6 mm. the ends of the iron wires *a* and *b* should become white hot but not hot enough to melt. If this spark is run at regular time intervals during a series of measurements and kept carefully adjusted it will give a very satisfactory source for a considerable time.

In cases where greater accuracy is desired a more reliable though a more elaborate spark arrangement shown in Fig. 45 may be used. *AB* is a brass tube about 3 cm. in diameter and 12 cm. long. *C* and *D* are two side tubes about 1.5 cm. in diameter and 6 or 8 cm. long. The iron wires *a* and *b* pass through glass tubes *t* and *t* to prevent sparking between the wires and the brass tube. These glass tubes in turn pass through ebonite plugs in the ends of the tubes. The joints are made gas-tight by sealing wax. The end of the larger tube at *A* is closed by a quartz window sealed to the end of the tube by wax. When any windows or lenses are required through which the ultra-violet light is to pass quartz must of course be used as ordinary glass absorbs the ultra-violet rays. The
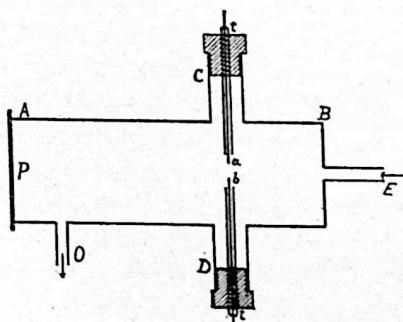
FIG. 45.

iron terminals are kept in an atmosphere of pure hydrogen by passing a continuous slow stream of hydrogen, which has been thoroughly dried, through this apparatus, entering at *E* and emerging at *O*. This hydrogen should also be thoroughly free from oxygen, for if any oxygen be present water vapor is formed by the action of the spark, and this

hinders the passage of the ultra-violet rays. Such an arrange-
ment, which is due to Varley, will be found very constant over
considerable intervals.

With either of these forms of spark to secure constancy the
current in the induction coil should be kept constant, the
spark length should be maintained at a constant length and the
spark should be run at regular time intervals, as far as
possible.

70. Ionization by Ultra-violet Light.—An ionization cham-
ber suitable for testing the ionization produced by ultra-violet
light is shown in Fig. 46, in which AB is a brass cylinder, of
which the length AB is about 6 cm. and the diameter AC 10
cm. An opening ab, 5 cm. in diameter, in the end is closed
by a quartz plate P sealed to the brass by wax. D is a side
tube 2 cm. in diameter and 5 cm. long, in the end of which an
ebonite plug fits. Through this plug passes a light brass rod K
on the end of which is a metal circular frame ff 6 cm. in
diameter, across which is stretched a fine copper grating con-
sisting of very fine wires not
more than 0.3 mm. in diameter.
This grating should be situated
not more than about a centi-
meter from the quartz window.
A zinc electrode H, 5 cm. in
diameter, is supported by a brass
rod which passes out through an
ebonite plug, which in turn fits
into a brass tube EF, soldered
into the end of the large cylinder

FIG. 46.

and about 5.5 cm. in diameter. This zinc plate may be adjusted
anywhere from 5 to 10 mm. from the wire grating. Before be-
ing placed in position this plate should be thoroughly cleaned
with emery paper so that it may present a bright, clean surface
on which the ultra-violet light is to fall. All the joints between
the ebonite and metal, etc., are made gas-tight by waxing. The
wire grating is connected through the brass rod K to the elec-
trometer while the zinc plate H is connected to the negative
pole of the battery, the other pole being to earth.
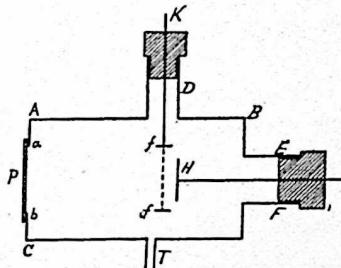
Set up the spark apparatus so that the source of ultra-violet light is at the principal focus of a convex lens of quartz, in order to obtain a parallel beam of ultra-violet light after passing through the lens. Allow this beam to pass into the ionization chamber through the window P and fall normally upon the zinc electrode H.

Start with the air in AB at atmospheric pressure. Run the spark a few times to secure regularity of action and then measure the current produced between the plate and the grating in the usual manner for different voltages on the plate H, and plot the usual voltage-current curve. Note that with even fairly high voltages it does not reach perfect saturation. Reverse the potential, making H positive and test the current. Note that in this case no current is, produced, whereas if Röntgen rays were used an equal current would be produced. This indicates that in the case of ultra-violet light the current is in only one direction and must be carried by negative ions only, for when H is positive the grating receives no charge. Reduce the pressure a few contimeters and determine the voltage-current curve with H charged negatively. Repeat this for various pressures below an atmosphere. Note at the lower pressures that the curves show the second rise corresponding to the production of fresh ions by collision. If, at these pressures, the potential on H which will cause ions to be produced by collision be changed to the same positive potential a current should be observed, for under these conditions both positive and negative ions are produced by the collisions of the negative electrons with the molecules, and therefore ions of both sign are present and a current may be obtained in both directions. Test this carefully at different pressures.

Replace the air by other gases in turn and repeat the experiments performed in air. Compare carefully the voltage-current curves obtained in the different gases.

Several other substances besides zinc exhibit this photo-electric effect, such as potassium, sodium, lithium, magnesium, etc. Copper, platinum, silver and a few other metals exhibit it to a less extent,

To obtain this photo-electric effect the surface of the zinc or other metal employed should be as clean and well polished as possible. If the surface becomes tarnished the effect is greatly diminished or even entirely destroyed.

71. Photo-electric Fatigue.—The rate of emission of electrons from some metals is much greater at the beginning of the exposure to the ultra-violet light than after the light has fallen upon the surface for some time. This effect is usually known as photo-electric fatigue. The cause of this phenomenon has not yet been thoroughly determined, as it appears to depend upon a variety of conditions, such as the nature of the metal employed, the nature of the gas surrounding the metal, the pressure of the gas and even the quality of the ultra-violet light used. It may easily be observed in the case of zinc in air at atmospheric pressure. Starting with a perfectly clean zinc surface in air at atmospheric pressure test the photo-electric effect at intervals extending over some time and note that the effect diminishes appreciably after the plate has been exposed to the light for some time.

72. Incandescent Solids.—Many years before the ionization theory of gases was advanced it was known that a red-hot or white-hot metal caused the air about it to conduct electricity. If a metal electrode be placed near to a metal wire and the latter be heated until it begins to glow a current through the gas will be produced and the electrode will receive a charge. The charge received by the electrode and the current depend upon several conditions, such as the temperature of the wire, the pressure and nature of the gas surrounding it and also the material of the wire. The behavior of hot metals and the gases surrounding them is very irregular, but it has been found that the gases surrounding these hot metals present all the characteristic properties of ionized gases. In general the results of experiments show that metals and carbon heated to incandescence in high vacua give off negatively charged carriers. The ratio of the charge to the mass of these carriers has been shown to be the same as for the cathode ray particles, and the electron liberated by ultra-violet light at low pressures.

This, along with other considerations, has led to the theory that these negative corpuscles are distributed throughout the volume of metals at all temperatures, but when the metals are heated to incandescence the corpuscles acquire sufficient energy to escape into the surrounding space.

At lower temperatures and higher pressures positive carriers are given off from some metals when heated. Although this question has been investigated to a considerable extent, yet the phenomena seem so complicated that no very definite explanation has as yet been arrived at. The results seem to indicate that the positive carriers are due in some way to a disintegration of the hot metal or to some chemical action and that the positive carriers are large compared with the negative corpuscles.

The general action of heated solids in this regard may be illustrated by the following experiments.

73. Heated Platinum.—The form of apparatus shown in Fig. 47 will be found convenient for the study of heated platinum. AB is a glass tube about 4 cm. in diameter and 10 cm. long. A fine platinum wire ab is fastened at the ends, by welding, to two heavier platinum wires cd, which are sealed through the glass at the ends of the tube. $PQRS$ is an aluminium cylinder from 2 to 3 cm. diameter surrounding the platinum wire and supported by an aluminium rod H, which is fastened to a platinum wire sealed through the end of the tube T. A couple of narrow slits should be cut in this cylinder opposite to one another so the wire may be seen as it is gradually heated up.

Connect through a suitable adjustable resistance R_1 and key K to the wires c and d a battery H_1 of large storage cells capable of producing a steady current of several amperes for the purpose of heating the wire ab. Connect the wire ab through one of the terminals c to one pole of a set of small accumulators H_2 and the cylinder PR to the electrometer in the usual way as shown in the diagram. Start with the vessel filled with air at atmospheric pressure and gradually increase the current through ab from the battery H_1 until ab begins to

glow. Make the pole of H_2 connected to ab the positive one and when the wire begins to glow observe that the cylinder receives a positive charge, indicating the passage of positive electricity from ab to the cylinder. Make ab negative and note that the cylinder receives no charge. This indicates that only positive electrification is given off at this temperature. Gradually increase the temperature of the wire and note that the positive charge received by the cylinder when ab is positive gradually increases until a maximum is reached at about the temperature of a yellow heat, and as the temperature is further increased the charge received by PR diminishes.

Starting again with the wire at a temperature of about a yellow heat, or a little above this, gradually exhaust the air from the vessel and observe the current between ab and the cylinder at the different stages. Note that for a consider-
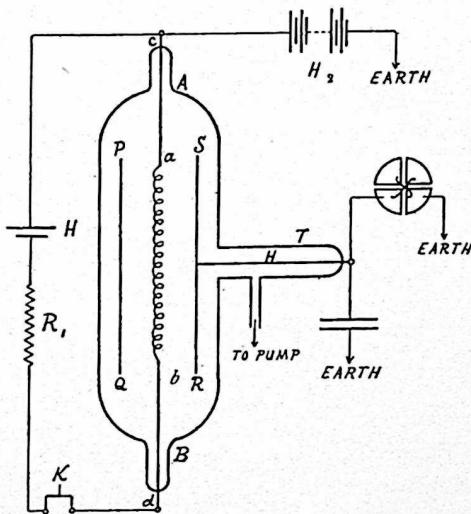

FIG. 47.

able range of pressure below atmospheric pressure no very great change of current takes place until a pressure somewhat below a millimeter is reached, when the gain of positive charge by the cylinder begins to diminish and finally when a very

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low pressure is reached the charge received by PR changes sign and finally reaches quite a high negative value, showing that the hot wire at this low pressure gives off negative electricity. In order of course to detect this the potential on ab must be negative and this should be carefully experimented on about the reversal point.

When the low pressure, at which the negative electricity is given off, is reached keep the pressure constant and measure the ionization current for different potentials between ab and PR and plot the current-voltage curve in the usual manner, which will be found to resemble the usual form of saturation curve.

If the platinum wire has not been heated before it will be found necessary to keep continuously pumping out the vessel at the low pressures to maintain the pressure constant, as the heating of the wire causes it to give off occluded gases which increase the pressure in the vessel. Similar measurements may be made with a fine copper wire in place of the platinum.
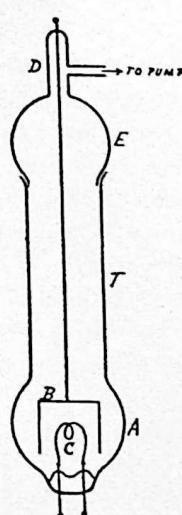
74. Heated Carbon.—Similar phenomena at low pressures may be observed in the case of heated carbon. The carbon filament from a small incandescent lamp may be utilized for this purpose. The thick filament from an 8-volt lamp will be found suitable, and it may be used without removing it from its fixtures in the lamp by breaking off the top of the lamp A (Fig. 48) and then carefully joining on a wide glass tube T which has first been drawn down to a smaller diameter and joined on to the tip of the lamp. After the joint is made it may be carefully blown out to a larger size so as to admit the electrode B, which surrounds the filament C. This electrode B consists of an aluminium cylinder which is supported by a rod sealed through the glass tube D. On the other end of D a bulb E is blown and the joint between this bulb E and the tube T is made with sealing wax as described in § 31.

Fig. 48.

The discharge of electricity by the carbon filament must be tested only at the low pressures, for in the presence of oxygen the carbon oxidizes at the high temperatures and would consequently be destroyed at the higher pressures. Test the discharge from the carbon at the low pressures as to whether it is positive or negative. Determine the current-voltage curve.

Substitute hydrogen for air in the vessels and repeat the experiments with both platinum and carbon and compare the results with those obtained with air.

In some of the above experiments it will be found that the current between the wire and the electrode is so large that it may easily be measured by means of a sensitive galvanometer. In these cases it will be found more convenient to use a galvanometer instead of the electrometer.

75. Ionization from Flames.—Flames form another very common source of ions. Gases surrounding flames contain ions and will conduct electricity. If two electrodes are placed some distance apart in an ordinary Bunsen flame quite an appreciable current is observed which may be measured by a galvanometer. If the air surrounding such a flame be drawn away from the flame it is found to be still conducting, as a gas ionized in any other manner would be. Ions are produced by a considerable variety of flames, but it is necessary for the flames to be of a comparatively high temperature. Low temperature flames do not produce ions. The ions produced by flames appear to be much larger than ions produced in other ways, for their velocity has been measured and found to be much less than that of other ions.

The experimental determination of the electrical conditions in flames is somewhat complicated by the fact that in order to make measurements metal electrodes must be used and when placed in the flame they become incandescent and give off electricity themselves, and it is difficult to separate this effect from the effects due to the flame alone. The following simple experiments will however serve to illustrate the electrical properties of flames.

Place an ordinary coal gas flame between two parallel metal

plates so that there is a space of half a centimeter or so on each side of the flame between it and the plates. Charge one of these plates to a high positive potential and the other to a high negative potential by a set of accumulators. Observe that the outer part of the flame where the most combustion takes place is drawn towards the negative plate while the interior or cooler part of the flame is attracted to the positive plate, showing that the hotter part is positively charged while the cooler part is negatively electrified.

In a Bunsen flame place the ends of two platinum wires and connect one of these through a sensitive D'Arsonval galvanometer to one pole of a storage battery of only a few volts and the other electrode to the other pole. Observe the current as measured by the galvanometer. Test this current for various positions of the electrodes in the flame and note that the magnitude and direction of the current depends greatly upon the relative positions of the electrodes.

Place the platinum electrodes some distance apart in the flame and note the current. Drop a few crystals of any of the ordinary salts, which volatilize when heated, into the flame between the electrodes and observe the sudden increase of current produced. The same effect will be observed if a solution of any of the salts be introduced by spraying into the flame.

Place a Bunsen flame at the end of a glass or brass tube 3 or 4 cm. in diameter and 30 or 40 cm. long and allow the other end of the tube to open into a fairly large sized electroscope. By an aspirator attached to another opening in the electroscope draw a slow current of air past the flame and into the electroscope. Charge up the gold leaf of the electroscope and observe that as the air current is passing the charge quickly disappears, showing that the air surrounding the flame is conducting and it retains its conductivity for a time after being removed from the neighborhood of the flame just as an ionized gas will do.

This conductivity of flames is often made use of in discharging an electrified body. If for instance any insulation has become charged up on the surface it will sometimes take

a long time for the charge to leak away, and in the meantime it will cause troublesome electrostatic disturbances. To get rid of this charge on the surface it is sufficient to simply pass a Bunsen flame quickly over the surface a few times (see § 15), when the conductivity of the flame will allow the charge to be conducted away through the flame. A flame furnishes a convenient conductor in this case, as good contact can be made over the whole surface of the insulation so as to completely get rid of the charge.

As pointed out previously (§ 15) the presence of flames in the neighborhood of insulated conductors is to be carefully avoided or otherwise the conductors will lose their charge through the conductivity imparted to the air by the flames.

CHAPTER VII.

IONS AS NUCLEI.

76. General Phenomena.—For some years before the ionization theory of gases was propounded it was known that if dust particles were present in a damp gas the water vapor would condense around these dust particles as nuclei when a sudden expansion of the gas took place. It had also been observed that if a highly charged electrode, such as the terminal of an influence machine or induction coil, were placed near a transparent steam jet a marked change in the jet occurred during the escape of electricity from the electrode. The steam condensed into fine drops, as could be shown by the increased opacity of the jet if its shadow were cast on a screen.

After the discovery of Röntgen rays it was shown that if a beam of the rays were allowed to fall upon the steam jet condensation took place. Since it had been proved that dust particles acted as nuclei of condensation some maintained that the condensation of the steam jet in the cases of the charged electrode and Röntgen rays was also due to dust while others explained the effect on the steam jet as due to the presence of ions. In 1897 and later C. T. R. Wilson proved by a series of valuable experiments that ions do act as nuclei on which water vapor will condense when moist air is suddenly cooled by expansion.

77. Expansion Apparatus.—The later and improved form of apparatus designed and used by Wilson is shown in Fig. 49. *A* is the vessel in which the expansion takes place. It consists of a heavy glass cylinder *ab* about 16 or 18 cm. in diameter and about 8 cm. in height. The ends of the cylinder are ground flat so that the brass plates *cd* and *ef* fit tightly against the ends. Between these plates and the ends of the cylinder thin rubber washers should be placed and the two plates drawn tightly together against the ends by six or eight

brass rods *rr* acting as bolts with nuts. If this does not make
the vessel air-tight the joints may be waxed. From the middle
of the lower plate *ef* a brass tube *T*, about 7 cm. in diameter
and 25 cm. long, leads. The lower end of this is closed by a
large rubber stopper *S*. This tube also contains a closely fitting
piston *P* which consists of a light brass tube with a hemi-
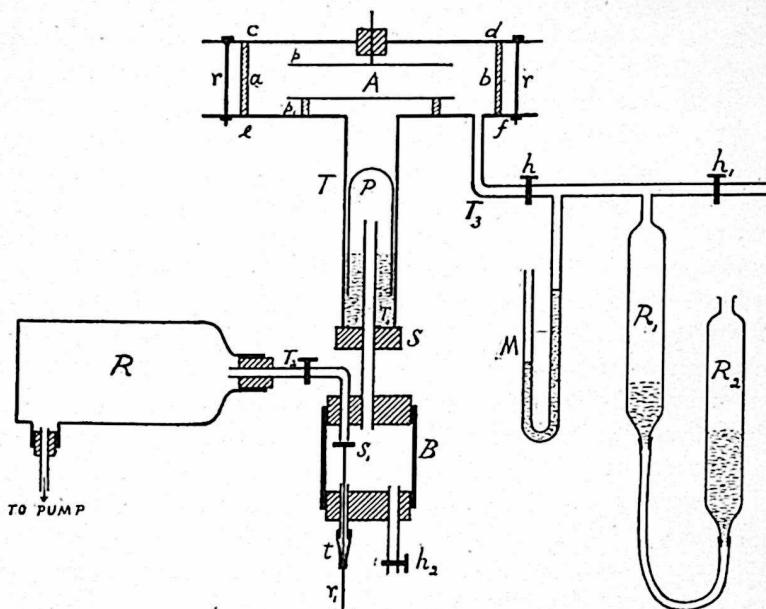
FIG. 49.

spherical top. This piston should be made to slide easily inside
the tube. Through the stopper *S* another glass or brass tube
leads into an air-tight chamber *B* and from this leads another
tube T_2 to a large glass receiver *R*, which is connected to an
air-pump. For this purpose a large glass bottle with two out-
lets may be used. The opening of the tube T_2 is closed by a
rubber stopper S_1 attached to the end of a rod r_1 which passes
out through a closely fitting tube in the bottom of the chamber
B. A piece of rubber tubing *t* should fit tightly over the end
of the tube and the rod r_1 so that the rod may be moved

through the tube without allowing air to enter B. The stopper S_1 and attached rod are held tightly against the end of the tube T_2 by a stiff spiral spring. From the upper chamber A another small glass tube T_3 leads to a manometer M by which the pressure in A may be measured when the tap h is open. R_1 and R_2 are two mercury reservoirs connected by a rubber tube by which the pressure in A may be regulated. The tap h_1 closes the tube. The shaded part in the tube T is filled with water which serves to keep the air in A saturated as well as to make a flexible air-tight joint between the piston P and the tube T.

Now suppose that the mouth of the tube T_2 is closed by S_1 and R is partially exhausted by the air-pump. Suppose the air in both A and B is at atmospheric pressure. If h_1 be closed and h opened and R_2 be lowered slightly, then the pressure in A will be slightly relieved and the piston P will rise a little until the pressure in A and B balance. Then if S_1 be suddenly withdrawn from the end of T_2 the air in B will suddenly rush into R and thereby lower the pressure in B to a point considerably less than that in A, and the piston P will be suddenly forced down against S. This results therefore in a sudden expansion of the air in A. The more rapidly this expansion takes place the better, and therefore the rod r_1 should be attached to a trigger arrangement with a strong spring so as to obtain a very sudden release and consequently a very sudden opening of T_2.

78. Production of Clouds.—Close the valve S_1 and the tap h_1, open the taps h_2 and h and by adjusting R_2 raise the piston P only a short distance in the tube T, so that only a small expansion will take place when P is forced down. Close the tap h; partially exhaust the reservoir R and suddenly open S_1. Observe the dense cloud formed in A. To observe this to the best advantage render the drops visible by brightly illuminating the space in A by a strong beam of light from an arc lamp, concentrated by means of a glass convex lens. This lens not only serves to concentrate the light, but also cuts out any ultra-violet light which would be apt to affect the results. Observe the cloud gradually fall. When the drops have

disappeared repeat the experiment, expanding the air in A again. Repeat this several times and observe that a cloud is formed each time, but that it gradually becomes less dense until, after a number of expansions, practically no cloud is formed. These clouds are due to the dust particles in the air around which the water vapor condenses and the dust is carried down with the drops and therefore after several expansions the air is finally freed from dust. After the air is thus practically freed from nuclei no cloud is formed if the amount of expansion is below a certain limit.

Even in air freed from dust particles clouds may be formed by expansion under certain conditions. The formation of a cloud in dust-free air depends upon the extent of the expansion. Wilson has shown that if v_1 is the volume of the air in A before expansion and v_2 the volume after expansion then if v_2/v_1 is less than 1.25 no condensation occurs in dust-free air; if v_2/v_1 is between 1.25 and 1.38 a few drops may be observed but as soon as v_2/v_1 becomes greater than 1.38 a dense cloud is formed on expansion even if no dust be present. Test these facts carefully by expansion. The amount of expansion depends upon the height to which P is raised, and since the volume is inversely proportional to the pressure the ratio of the volumes before and after expansion may be determined by observing the pressure as indicated by the manometer M before and after expansion.

Completely free the space A from dust by repeated expansions. Then adjust by trial the height of the piston P so that the ratio of v_2/v_1 will be less than 1.25 and observe on expansion whether any cloud is formed. By careful adjustment gradually increase this ratio and observe the result as regards condensation. By a series of trials verify the results stated above.

79. Ions as Nuclei.—If the gas in A be acted upon by an ionizing agent, such as Röntgen rays a change occurs. Pass a horizontal beam of Röntgen rays through the air in A and repeat the experiments of the last paragraph, and observe that for values of the ratio v_2/v_1 below 1.25 no cloud is formed as

before. But between the values 1.25 and 1.38 a dense cloud is formed when the rays are acting where only a few drops were observed before when no rays were acting. This indicates that the ions act as nuclei on which the water vapor condenses.

That the formation of the cloud in this instance is due to the presence of the ions and not to some other possible action of the rays may be easily proved by the following experiment: Place in the chamber A two insulated parallel plates p and p_1 as indicated in the diagram, about 5 cm. apart. Establish a potential of about 400 volts between these plates. This electric field should remove the ions as soon as formed. With this large potential between the plates pass the rays through as before and observe that with the expansion that would produce a cloud with no field on there is practically no more condensation than when no rays acted at all. Note that as soon as the plates are disconnected from the battery the same expansion will produce a dense cloud. This shows that the dense cloud which is formed by the rays when there is no field on is due to the presence of the charged ions, for when they are removed by the electric field the cloud is not formed.

It can easily be shown also that these drops of water formed by the action of Röntgen rays are charged, for if an electric field be applied to them after they are formed they will move under the influence of the field. Allow the rays to ionize the air between the plates in A as before but without any electric field on and produce a cloud by a suitable expansion. As soon as the sudden commotion in the air caused by the expansion subsides apply a strong electric field between the plates and, if the field is strong enough, it may be observed that some of the ions move towards the upper plate, while the others move more quickly downwards than they would do simply under the action of gravity. If the field be reversed the direction of motion will be reversed. This action of the electric field on the drops shows that they carry a charge and that there are charges of both signs present, showing that both the positive and negative ions act as nuclei. A cloud which is formed without the

action of an ionizing agent will not be affected by an electric field.

Wilson has also shown by means of a special form of expansion chamber that water vapor condenses more easily around the negative ions than on the positive. When v_2/v_1 exceeds the value 1.25 and reaches the value 1.28 a large amount of condensation takes place around the negative ions, but very little condensation takes place on the positive ions until a value of 1.31 is reached. This is a confirmation of the theory that the cause of the greater diminution of the velocity and rate of diffusion of the negative ion in moist gases is due to the negative ion becoming more easily loaded with moisture than the positive ion.

80. Ions from Other Sources as Nuclei.—Remove the plates p and p_1 from the expansion chamber A and replace the plate cd by a similar one which has an opening in it covered with a quartz window to admit ultra-violet light. Inside of A place a polished zinc plate some distance below the window. Allow ultra-violet light to pass through the window and fall on the plate and repeat the experiments described in the first part of § 79, using the ultra-violet light in place of the Röntgen rays and observe the formation of the cloud, which indicates that the ions produced by ultra-violet light will act as nuclei in a manner similar to those produced by Röntgen rays.

Again remove the plate cd with the quartz window and replace it by another similar one from which a thin platinum spiral is suspended, with the two ends of the wire passing out through small insulating plugs so that the wire may be connected to a battery by which it may be raised to incandescence. Heat this platinum wire in the usual way by a storage battery and repeat the experiments described in the first part of § 79, using the charged nuclei produced by the hot wire in the place of the ions produced by Röntgen rays. Note the values of v_2/v_1 necessary to produce the cloud when the wire is at different temperatures. Since at the lower temperatures positive ions are given off by the wire while at the higher temperatures negative ions are emitted, a difference between the expan-

sions necessary to produce condensation around the positive and the negative ions may be noted here, as at the different temperatures one kind predominates over the other. Carefully observe this difference.

81. Charge Carried by an Ion.—This property of ions to act as condensation nuclei has been utilized to determine the absolute value of the charge carried by an ion. The method is not a very simple one and had better be left by the student until further work has been done and more experience gained in this subject. The general principle will however be described here.

When an expansion takes place in ionized air water drops form around the ions and fall under the action of gravity. Sir George Stokes has shown that if a drop of water of radius r falls through a gas of viscosity μ then the velocity v with which the drop falls is given by the equation

$$v = \frac{2}{9} \cdot \frac{gr^2}{\mu},$$

where g is the acceleration of gravity. The velocity v can be measured by observing the rate at which the cloud falls under the action of gravity, and since μ is known for air and g is also known, therefore r may be determined. If m is the mass of water deposited and n the number of drops per c.c., then $m = n \times \frac{1}{3}\pi r^3$, since the density of water is unity. From well-known thermal considerations the amount of water vapor deposited from a gas when a known expansion occurs can be easily calculated, and therefore m may be determined. Knowing m and r the number of drops n, which is the same as the number of ions, is easily calculated.

Let two parallel plates be placed d cm. apart in the expansion chamber A (Fig. 49), and let a potential difference V, small compared with that necessary to produce saturation, be applied to them. Then if the sum of the velocities of the positive and negative ions per unit potential difference be u and the charge on each ion be e the current i per square centi-

meter of cross section of the plates is given by

$$i = \frac{nuVe}{d},$$

since n is the number of ions per c.c. and the current is proportional to the total charge ne and the velocity uV and inversely proportional to d. The value of n has been determined from the expansion, and u is known for any value of d (§ 66). The value of i can be measured in the usual way by the electrometer and d and V can be measured. Therefore e may be calculated.

By the latest determinations of J. J. Thomson he has shown that

$$e = 3.4 \times 10^{-10} \text{ electrostatic units.}$$

He has also shown that the charge carried by the ion in hydrogen or oxygen has the same value and that it does not depend upon the source by which the ions are produced. These results seem to indicate that the charge carried by a gaseous ion is the same under all circumstances, and it appears that it might be taken as an invariable and fundamental unit of electricity.

PART II.

RADIO–ACTIVITY.

CHAPTER VIII.

INTRODUCTORY EXPERIMENTS ON RADIO-ACTIVE SUBSTANCES.

82. Discovery of Radio-activity.—The discovery of Röntgen rays and their close connection with phosphorescence led physicists to enquire whether any natural substances, especially those which exhibit phosphorescence, were capable of producing radiations of a similar nature. Several substances were examined by different experimenters, but the first discovery of importance in this regard was made by M. Henri Becquerel in 1896, who found that the double sulphate of uranium and potassium emitted a radiation which produced an effect upon a photographic plate enclosed in black paper similar to the effect produced by Röntgen rays. He later examined other compounds of uranium as well as the element itself and found that they all possessed this power. The extent of the action on the plate does not depend upon the particular combination in which the uranium occurs, but entirely upon the amount of uranium present in the compound, which indicates that the radiations result from the uranium itself and not from the fact of its association with other substances.

Although the connection between Röntgen rays and phosphorescence pointed the way to the discovery of these radiations from uranium, and notwithstanding that they were first attributed to phosphorescence, it has since been shown that there is no connection between these rays emitted by uranium and its phosphorescence, for some compounds which are not phosphorescent emit the rays.

83. Warning.—Before proceeding to use the various radio-active substances with which we will have to do a timely caution must be given so as to prevent serious difficulty later. In handling these radio-active substances the *greatest care* must be taken not to spill the *slightest trace* of them, for if they become scattered round the laboratory, even to the slightest extent, the room will become so contaminated that after a time the air of the room will be so radio-active that no fine measurements or accurate work of this nature can be done in it.

In the cases of radium, thorium or actinium great precautions must be taken to always keep these substances tightly enclosed in an air-tight receptacle even while working with them, for as we shall see later they give off a radio-active gas which will cause the walls and other bodies in the room to become radio-active. This radio-activity cannot be got rid of for years. This latter precaution need not be taken in the case of uranium and its compounds.

84. Photographic Action of Rays from Uranium.—Wrap a photographic plate in ordinary black paper. Spread a few grams of uranium oxide on a thin sheet of paper in a layer covering an area of 6 or 8 cm. square. Lay two or three opaque articles, such as small pieces of metal, on the black paper covering the plate on the film side of the plate, and on top of these pieces of metal place the sheet of paper containing the uranium oxide. Lay this away in a perfectly dark room for about twenty-four or thirty-six hours. Then develop the photographic plate in the ordinary way, and observe that the plate is darkened except where the opaque bodies cast a shadow. The uranium thus gives off a radiation which affects the plate but differs from light in the fact that it penetrates the black paper, although it will not penetrate the metals. The action is however very weak, as it takes several hours to produce any impression. If the uranium oxide and plate had been left for only an hour or two practically no effect would have been observed on account of the weak action of the rays. The same experiment may be repeated using other compounds of uranium, such as the sulphate, etc.

85. Power of Uranium Rays to Discharge an Electrified Body.—Using an electroscope of the form shown in Fig. 14 cut a hole about 5 cm. square in the base plate and cover this opening by a very thin sheet of tissue paper simply to prevent air currents inside the electroscope. Cut two sheets of brass or zinc 15 cm. square and 2 or 3 mm. thick. In one of these cut a central square hole about 5 cm. square. To the other plate solder or rivet two short upright pins, and in the plate from which the hole is cut bore two holes corresponding exactly in position with the pins in the other, so that the two plates may be fitted together always in a definite relative position. These, when placed together, will form a shallow receptacle of definite area which may be used to hold the uranium compound.

Place a few grams of uranium oxide in a uniform layer in this receptacle and place it immediately below the opening in the electroscope. Repeat in detail the experiments described in § 46, using the radiations from uranium in place of the Röntgen rays. Note that the effects produced are practically identical with those produced by Röntgen rays. The radiations from the uranium are however of a much weaker nature than Röntgen rays.

Using the apparatus represented in Fig. 28 substitute for the Röntgen rays a few grams of uranium oxide contained in a small shallow trough, which may be placed either in the bottom of the tube *AB* or just below an opening cut in the bottom of *AB*. It is advisable to cover the trough with a sheet of thin tissue paper as a precaution in case the air current through the system should accidentally become strong enough to blow the oxide out of the trough.

Repeat in detail the experiments described in § 47, using the uranium radiations in place of the Röntgen rays. In cases corresponding to the stoppage of the Röntgen rays the uranium will of course have to be removed from *AB*. Observe that the effects produced by the uranium radiations are similar to those produced by Röntgen rays.

These experiments indicate clearly that uranium oxide emits

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some sort of a radiation which produces conductivity in a gas similar to that produced by Röntgen rays. This conductivity of the gas persists for a time after removal from the direct action of the rays and may be transmitted from one point to another along with the air. It may also be removed by mechanical or electrical means in the same way as that produced by Röntgen rays.

86. Ionization Current Produced by Uranium. *Apparatus.* —Arrange a system as shown in Fig. 50. *AB* is a rectangular box made of metal (zinc about 1 mm. thick is suitable) and should be about 25 cm. each way. *C* is a metal plate about 16 cm. square resting on insulating pillars, and is connected to
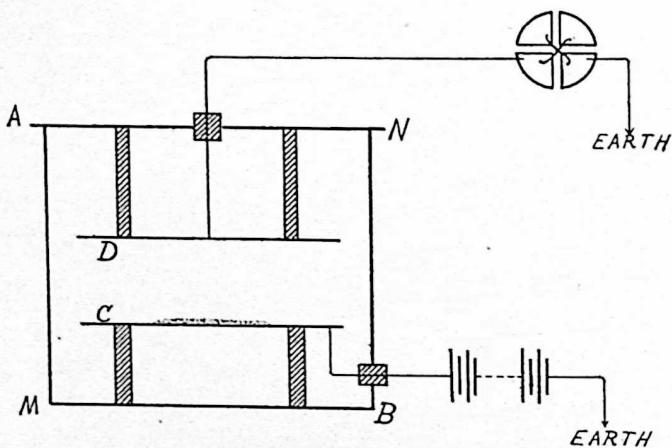
FIG. 50.

one pole of a battery of small accumulators as shown. *D* is a similar metal plate parallel to *C* and suspended by four ebonite rods from the top of the box. It is connected by a wire, passing out through an ebonite plug, to an electrometer in the usual manner. The top of the box may be fitted so that it can be lifted off and the whole of the upper part of the system removed if desired. One side of the box should be fitted with a door about 20 cm. square, which ought to fit closely when closed.

Current-voltage Curve.—Adjust the distance between the plates C and D to about a couple of centimeters by adjusting the height of C. On C place centrally the double plate receptacle, described in the last paragraph, containing a layer of the uranium oxide. On insulating the electrometer quadrants it will be observed that they immediately begin to charge up, indicating the presence of an ionization current between the plates. Measure this ionization current in the usual way for different voltages applied to C. Plot the current-voltage curve and observe that it is of the same form as shown in Fig. 32.

Current and Distance Between the Plates.—Determine the current-voltage curve for different distances of the plates apart varying from about 0.5 cm. to 5 cm. Note that they all follow the same general form, but that the saturation current increases as the distance between the plates increases. Plot a curve showing the relation between the saturation current and the distance between the plates. Note that the curve is not a straight line.

Current and Thickness of Layer of Material.—Place the plates a given distance apart, say about 2 cm., and place a sheet of note paper in the bottom of the receptacle for holding the oxide, and dust, by means of a fine wire gauze, a uniform and very thin layer of uranium oxide on the sheet of paper and measure the saturation current. Then increase the thickness of the layer a little by dusting some more oxide on the paper and measure the saturation current again. Repeat this a number of times, increasing the layer a little in thickness each time. Weigh the sheet of paper before starting the experiments and then weigh it and the contained oxide each time. Observe that the saturation current increases with the increase in the amount of oxide used. At first with thin layers the current is practically proportional to the quantity of oxide, but after the layer becomes thicker the current does not increase so rapidly with increase in thickness. Plot a curve showing the relation between the current and the quantity of oxide used.

Current from Different Compounds. — If different com-

pounds of uranium, such as the oxide, sulphate, chloride, etc., are available measure the saturation currents produced by equal quantities of these compounds under similar conditions and compare them. If it is convenient samples of these different compounds may be analyzed and the quantity of uranium present in each determined. If this is done it will be found that the current produced for a given weight of compound depends not upon the nature of the compound but upon the quantity of uranium present in it.

Current and Time.—Select a given specimen of any of the radium compounds, say uranium oxide, and test the saturation current produced by it between the plates at a given distance apart and repeat this test under exactly the same conditions each day for several days. It will be found that if all the conditions are kept constant the current will not change, showing that the radiations do not change with time. This will be found to be still true, even if the test is extended over many months.

Current in Different Gases.— Make another ionization chamber on the same principle as the one shown in Fig. 50, but instead of the enclosing vessel being a rectangular box make it of a brass cylinder about 15 cm. in diameter and the same height. The two ends may be fitted and then all the joints made gas-tight with wax. The uranium oxide may be placed on the plate C from the top and then the top plate which supports D put in place and waxed. The plates C and D should be about 3 or 4 cm. apart. Such a vessel may be filled with any gas and the current in it measured. Fill this vessel with any gases which may be available in turn, and measure the saturation current in each gas at atmospheric pressure and compare them. As in the case of Röntgen rays it will be found that the current depends very much upon the nature of the gas.

Conclusions.—The results of these experiments along with others which might be performed on uranium and its compounds show that the uranium emits spontaneously a radiation without the aid of any outside agency which ionizes a gas

in a manner similar to other ionizing agents already studied. This radiation belongs to the uranium itself and not to the substances with which it is associated. It depends upon the amount of uranium present in the compound and it does not deteriorate with time. Uranium and other bodies, which we shall see later possess similar properties, are called *radio-active* bodies and this form of radiation is called *radio-activity*. This term in its strict application is applied only to such bodies as are naturally and permanently radio-active, that is, which spontaneously emit such radiations, and not to such substances as may acquire this property temporarily by the action upon them of some outside agency.

87. **Other Radio-active Substances.** *Thorium.*—The discovery of the radio-activity of uranium naturally led to the examination of other substances to ascertain if any of them possessed similar properties. The element thorium and its compounds were found to possess radio-active properties, the photographic action being however weaker than that of uranium, while the ionizing power was about equal to that of uranium.

Mme. Curie then undertook a very systematic examination of a large number of mineral compounds containing uranium and thorium. Using the electrical method of examination she measured the current produced between two parallel plates by a given amount of each of the minerals. The results showed that all these minerals containing thorium or uranium were radio-active, but the most important point observed was that several specimens of pitch-blende (uraninite), as well as other minerals, were several times more active than uranium itself. Now if uranium be mixed with an inactive substance the activity will be less than that of the uranium alone, owing to the fact that some of the rays are absorbed by the material with which the uranium is mixed. It was at first thought that this abnormal activity of some of the minerals might be due to the particular chemical combination in which the uranium existed, but this was disproved by preparing one of these compounds artificially, when it was found to possess only the normal

amount of activity which would be expected from the amount of uranium it contained. This led to the conclusion that there must be some other and more active substance in pitchblende. M. and Mme. Curie investigated this question chemically and found two new active bodies.

Polonium.—The first of these substances to be separated by purely chemical means is much more active than uranium and differs from it in the essential particular that its activity is not constant but gradually dies away with time. It also differs from the other radio-active substances in the nature of the radiations given out, which will be discussed later. To this substance the name polonium was given.

Radium.—The other active substance discovered in pitchblende is enormously more active than uranium. In its pure state it is about a million times more active and consequently was given the name radium by the discoverers. Radium is probably the most remarkable and interesting of all the radio-active substances, and by the study of its properties an enormous amount of information has been obtained in regard to the most remarkable processes going on in nature in connection with these radio-active bodies.

The quantity of radium existing in pitchblende is almost infinitesimal, about a ton of pitchblende containing only a few milligrams of radium. The chemical properties of radium are similar to those of barium and it is separated from the mineral pitchblende by the same process as is used in the separation of barium.

Radium is found in varying quantities in a number of minerals and in various parts of the world, but the chief source at present known is in the pitchblende found in Bohemia.

In practice radium is not separated from the compound, but is usually made use of in the form of radium bromide, and what is often called pure radium is usually pure radium bromide. It also forms other compounds such as the chloride, sulphate, etc.

The method by which radium and polonium were discovered marks a great advance in the methods of analysis and of de-

tecting the presence of new bodies, for it was purely by their radio-active properties that these substances were discovered. They were entirely unknown before, and being in such minute quantities they might have continued to escape detection for a very long time, but their intense radio-active properties indicated their presence and then it was possible to attack them by chemical methods and separate them. This is very analogous to the methods used in spectrum analysis.

Actinium.—Not long after the discovery of radium another substance was found in some of the residues from pitchblende to which the name actinium was given. The properties of actinium are very similar to those of thorium, but the former is very much more active than the latter.

88. Current Produced by Other Radio-active Substances.— Obtain small quantities of thorium, actinium and radium compounds. Radium is obtainable only in very small quantities and is very expensive, but the other substances can be obtained in somewhat larger quantities. In a thick lead or brass plate cut a groove about 2 mm. deep by 5 mm. wide and 20 mm. long. In this place the specimen of radium. Over this, and flat on the plate, place a thin sheet of mica as thin as is obtainable and carefully wax the edges down so as to be gas-tight. This precaution must be taken to prevent the escape of the gaseous emanation (see Chapter XIII), which is continually being given off by the radium. Place this plate in the place of C (Fig. 50), and with a distance of about 2 cm. between the plates measure the ionization current produced. Determine the current-voltage curve for the specimen.

Make similar receptacles for holding the thorium and the actinium compounds, but these may be made larger as these substances may be obtained in larger quantities. These should be carefully sealed up also to prevent escape of gaseous emanations. Measure the current produced by these specimens also and determine the current-voltage curve in each case.

Compare the saturation currents produced by equal weights of these different specimens with that produced by the same weight of uranium. Measure the activity of any other samples

obtainable such as pitchblende, etc., and compare them all with a given equal weight of uranium.

89. Steady Deflection Method of Measuring Ionization Currents.—With this amount of data in regard to radio-activity at our disposal another and very useful method of measuring ionization currents may be introduced with advantage at this stage. The ordinary method of measuring ionization currents by the rate of movement of the electrometer needle, which we have used up to the present, depends upon certain conditions being fulfilled and in some cases possesses certain disadvantages. In order that the rate of movement of the needle may be proportional to the ionization current the capacity of the system must remain constant. If the current increases to a great extent the rate of movement becomes too rapid to be measured with accuracy and the capacity has to be increased to diminish this rapid rate of movement to a readable amount. This involves a comparison of capacities which is generally a troublesome task. Again the rate of movement method requires considerable time to make the observations, and therefore in some measurements when rapid changes are taking place it is practically useless. A steady deflection method has been developed by Bronson which overcomes these difficulties and has proved very satisfactory in practice.

Theory of Method.—If the air between two plates A and B (Fig. 50 (a)), connected respectively to a battery and an electrometer in the usual manner, be ionized by a radio-active body placed on A the electrometer will continue to charge up and the deflection of the needle increase in proportion to the voltage to which the quadrants become charged. If the pair of quadrants connected to B be connected to earth through a very large resistance R, then some of the charge received by the quadrants will leak to earth through this resistance. The quadrants will therefore continue to charge up and the deflection of the needle increase until the rate of supply of electricity to the quadrants is equal to the loss through the resistance, that is, the current through the resistance R is equal to the ionization current between the plates A and B. When this

stage is reached the deflection of the needle will remain constant since the potential of the quadrants remains steady. If the high resistance R obeys Ohm's law the current through R will be proportional to the potential of the quadrants, and therefore to the deflection of the needle since the deflection is proportional to the potential. Therefore since the current through R and the ionization current are equal this deflection will be proportional to the ionization current.

Since the ionization currents are usually so extremely small and the current through R is the same as the ionization current the resistance R, as will be seen from the following simple calculation, will have to be very large. Take as an example the typical case cited in § 20. The current to be measured is 9.2×10^{-13} ampere. Suppose that a steady deflection of 100 scale divisions is desired. This corresponds to a rise of potential of $\frac{1}{6}$ of a volt in this case and therefore the resistance R required will be $\frac{1}{6} \div (9.2 \times 10^{-13})$ which equals a resistance of 180,000 megohms. Ordinary liquid or carbon resistances of this order of magnitude are not satisfactory for this purpose, as they are somewhat unreliable. What may be termed an air resistance has been found to be most suitable. This consists of two parallel plates C and D (Fig. 50 (a)) in air, on the lower one of which there is placed a layer of radio-active material and the connections made as shown in the diagram. The charge received by the plate B and the electrometer system of which C is a part leaks away to earth through the air between the plates C and D in consequence of the conductivity of this ionized air and when the rate of loss is equal to the rate of supply a steady deflection will result. Such an air resistance obeys Ohm's law over a considerable range for the potential acquired by the plate C is small, being usually only a fraction of a volt and therefore below the saturation voltage. The current between C and D being thus below saturation will correspond to the steep part of the current voltage curve (Fig. 32), in which the current is proportional to the potential. The steady deflection being proportional to the potential will therefore be proportional to the current.

Calibration.—This proportionality should be carefully tested and the range on the scale determined over which it holds true for any particular setting of the scale. This may be done by placing a constant source of ionization such as uranium oxide
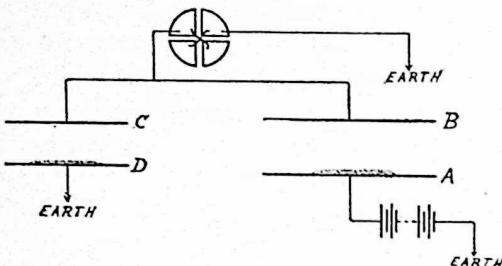
FIG. 50*a*.

on the plate *A* (Fig. 50*a*) and applying small known voltages much below the saturation voltage where the current between *AB* is known to be proportional to the voltage and observing the steady deflection. The test can be carried further for greater deflections by testing several small specimens of uranium oxide on the plate *A*, first separately and then in groups, the sum of the currents for the separate specimens being equal to the current for these specimens tested in groups.

If a straight scale be used the reading on the scale will of course not be proportional to the angle of deflection beyond an angle of a certain magnitude, but the proportional reading may be extended over a greater range by fixing the scale on a suitable support, so that instead of being exactly perpendicular to the line joining its central point to the electrometer needle it may be turned at a small angle to the perpendicular position, and it may even be bent to a slight curve to approach the circular form. These adjustments have to be made by trial in each particular setting.

Standard.—The plates *C* and *D* should be made as nearly as possible identical, for on account of the contact difference of potential between the plates due to any difference in their surface the needle will show a small steady deflection even when

there is no radio-active matter between A and B. This may be eliminated to a great extent by making the surfaces as nearly alike as possible as regards material, etc.

The radio-active material on the plate D used by Bronson in his early investigations of this method was radio-tellurium obtained as a coating on a bismuth plate prepared by the method of Marckwald. This plate was covered by a very thin sheet of aluminium foil and the plate C made of aluminium to eliminate the effect of any contact difference of potential. The plates C and D should be enclosed in a sealed vessel so as to keep them from any outside disturbing influences. Radium or other constant sources of radiation contained along with the plates in a sealed vessel may however be used. To be satisfactory they must remain perfectly constant.

Advantages of System.—This system of measuring ionization currents has several advantages over the rate of movement method. One decided advantage is the rapidity with which measurements can be made. The needle takes up its steady position rapidly and one does not have to wait on the long time of swing and the return to zero after each observation, or even the time required to pass over a given distance to determine the time rate. Any change in the current is rapidly indicated by the needle taking up a new steady position. Readings have been taken under some circumstances as quickly as once every five seconds. This is of great advantage in measuring rapid changes of activity such as will be discussed later. The readings may also be taken over a large range of currents without altering the sensitiveness of the electrometer and without any alteration of capacity of the system, for in this method the deflection is independent of the capacity. The potential of the electrometer system in this method is not continually increasing at a time rate due to a constant supply of electricity as in the rate method, but the electrometer system constitutes one point in what is practically a continuous closed circuit and when the rate of supply is equal to the loss the potential of this point is constant and independent of the capacity. The needle there-

fore takes up a steady position due to the steady difference of potential between the quadrants. Consequently comparative measurements of current by this method do not require any determination of capacities, even though the capacities may be changed.

CHAPTER IX.

COMPLEXITY OF RADIATIONS.

90. Absorption of Rays from Uranium by Solid Bodies.— In the ionization chamber (Fig. 50) place the plates B and C about 2 cm. apart and on C place in the usual way a thin layer, of not more than 0.5 mm., of uranium oxide. Measure the saturation current by the electrometer. Then place a thin sheet of aluminium foil, not more than .0005 cm. in thickness, over the oxide and measure the saturation current again. Over this place a second sheet of foil of the same thickness and again measure the current. Repeat this, adding a sheet at a time until ten or a dozen sheets have been added. Observe that for the first four or five sheets (the number will depend upon the thickness* of the foil used) the saturation current, which is a measure of the intensity of the radiation, falls off rapidly in a geometrical progression with the increase in the number of sheets, that is, according to an ordinary absorption law for any sort of radiation in general. When about four or five sheets have been added the intensity will have been reduced to probably about one twentieth of the original value, while the addition of the others produces a very slight effect, if any, in reducing the intensity of the radiations. After about four or five it requires a comparatively large number of sheets to produce much effect in this regard. It will be found that it will require probably from seventy-five to one hundred thicknesses of foil to reduce the intensity of the remaining radiation to half its value. These numbers that are given are of course only approximate to serve as a guide and will depend upon the exact thickness of foil, etc.

These results indicate that the radiations given off by

* The thickness may be determined very approximately by cutting exact squares of foil of known area and weighing a given number of them and, knowing the density, the thickness may be determined.

uranium must be complex, consisting of at least two types of rays, one of which is capable of passing through only a small thickness of aluminium foil, while the other type is much more penetrating. The first type, or easily absorbable rays, have been given the name α rays, while the more penetrating type are called β rays. The α rays are completely cut off by a thickness of about .002 cm. of aluminium and consequently after this thickness is placed over the uranium only the β rays get through.

Using the same thin layer of uranium oxide cut off all the α rays by a sheet of aluminium about .002 cm. thick and then further test the absorption of the β rays by adding increasing thicknesses of aluminium foil until the β rays are completely cut off and note carefully the decrease of ionization current with increase of thickness of absorbing material. Note that it requires a very much greater thickness of aluminium to completely cut off the β rays than it does to absorb the α rays.

From these measurements it will be seen that by far the greater portion of the total ionization produced by the radiations from uranium is produced by the α rays, for before any aluminium is introduced the ionization is produced by the joint action of the α and β rays and we have seen that only about five thicknesses of aluminium foil completely cut off the α rays but have little effect on the β rays, and when the α rays are completely absorbed and only the β rays are acting the total ionization is reduced to a small fraction of the original when both α and β rays were acting. This will be discussed a little more fully in the following chapter.

Obtain a large quantity of uranium oxide, as much as 75 or 100 grams if possible. Make a receptacle for it in a metal block so that it may cover an area of about 20 or 25 sq. cm. and deep enough to hold the quantity available. Measure the ionization current produced by the radiations from this in the manner described above. Test both the α and the β radiation. Add sheets of tinfoil until both the α and β rays are completely cut off and the electrometer will then show practically no ionization unless it is extremely sensitive. Now set

up a gold leaf electroscope of the type shown in Fig. 14. Measure its rate of leak due to the natural ionization of the air (see Chapter XVI). Place underneath the electroscope the specimen of uranium oxide covered with the tinfoil and observe that although the electrometer showed no ionization in the ionization chamber the electroscope shows a considerable rate of leak, indicating that a radiation of some sort has penetrated the tinfoil and is ionizing the air in the electroscope. The delicate electroscope detects this weak ionization, while the electrometer may not be sufficiently sensitive to do so. Measure this rate of leak and, subtracting the natural rate of leak of the electroscope, the rate of leak due to this radiation is obtained. Now add thin sheets of lead, about 0.5 mm. thick, one sheet at a time, and after adding each one measure the rate of leak, that is the ionization, and observe that the radiation is gradually cut down in intensity by the addition of the lead, but that it requires a thickness of a centimeter or more of lead to completely cut off this radiation.

These results indicate that in addition to the α and β rays given off by the uranium there is an extremely penetrating radiation emitted which will pass through a considerable thickness of a very dense substance like lead and which produces ionization of a very weak character compared with that produced by either the α or β rays. These very penetrating rays are called γ rays. The radiation emitted by uranium is therefore complex, consisting of three types of rays differing very much from one another in penetrating power.

91. Rays from Thorium and Radium.—Using specimens of thorium oxide and of radium bromide repeat the experiments of the last section on the α and β rays. As in the case of uranium use a comparatively thin layer of each specimen. The ionization chamber of Fig. 50 will have to be modified slightly to suit these experiments as these substances continuously give off gaseous emanations (Chapter XIII), which produce ionization independent of that produced by the ordinary rays emitted by the thorium or radium. To avoid this complication the emanation must be removed. To do this introduce an inlet -

tube about 8 mm. in diameter in the upper part of the side *AM*, and two or three outlet tubes in the side *BN*, distributed over the part opposite the space between the plates. Connect these outlet tubes in parallel to a single tube leading to a water exhaust pump or other aspirator so as to draw a slow steady current of air through the vessel. As this emanation is carried out through the water pump special precaution must be taken to prevent the escape of any of this emanation into the room. The discharge water and accompanying air from the water pump should therefore be led off by a special tube to the air outside the building. If this precaution is neglected the room will become permanently contaminated by this emanation so that after a short time the room and contents will become radio-active and no accurate work of this kind can be carried on in it. The nature and action of these emanations will be discussed more in detail in a later chapter.

The results of the experiments mentioned at the beginning of this paragraph will show that both thorium and radium compounds emit α and β rays of a similar nature to those emitted by uranium.

Using a large quantity, about 75 or 100 grams, of thorium oxide repeat the experiments of the last section on the γ rays and note that thorium also gives off the penetrating γ rays. The same experiments should be performed with radium bromide, but in this case a large quantity of radium is not necessary even if it were available, as these penetrating γ rays may quite easily be detected by using only a comparatively small quantity of radium. This is due to the fact that radium is so very much more strongly radio-active, weight for weight, than either uranium or thorium. If only a thin layer of the two latter substances be used only a very small amount of γ rays are emitted and the ionization produced is very weak, as the γ rays are not strong ionizers. But if a large quantity be used in a thick layer, then, since the γ rays are very penetrating, those from the lower portions of the thick layer are able to pass up through the material without being absorbed to any great extent. By thus increasing the thickness of the layer

the quantity of γ rays is increased practically in proportion to the thickness of the layer up to a certain limit, and therefore the ionization is increased sufficiently to be detected. In the case of radium however it is so strongly radio-active that even a thin layer emits a sufficient quantity of γ rays to be detected.

92. **Magnetic Deflection of β Rays.**—The discovery in the year 1899 that some of the radiations from radio-active bodies could be deviated by a magnetic field caused a considerable advance in the differentiation of these rays and the determination of their true nature. It was found that the β rays emitted by the various radio-active substances were affected by a magnetic field in a manner similar to that in which cathode rays are affected by a corresponding field. This may be shown very conveniently in the following manner: Place a small quantity of radium bromide on a thick lead block A (Fig. 51), between two parallel thick lead plates BB, which should be about 4 cm. high and 2 cm. wide and about 0.5 cm. apart. Above these lead plates place two insulated metal plates PP', the same distance apart as the lead plates and about 7 cm. high and 5 cm. wide. The rays from the radium ionize the gas between the plates and the presence of the rays between these plates may be detected by measuring the ionization current between P and P'. Place this

FIG. 51.

arrangement between the poles of a strong electro-magnet so that the magnet field may be applied perpendicularly to the plane of the paper, that is, parallel to the plane of the plates BB. The dotted line in the diagram represents the outline of the pole-pieces of the magnet. A slow current of air should be drawn through the space between the plates BB to prevent the emanation from diffusing upward between the plates P and P'. Measure the saturation current between P and P'. This will be almost wholly due to the α and β rays as
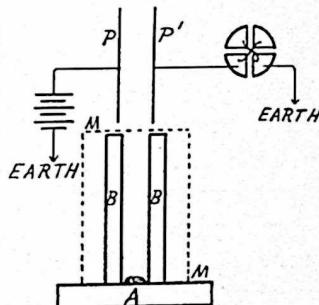
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the ionization due to the γ rays is so small for a thin layer of material that it is negligible in comparison with that due to the α and β rays. Place a sheet of aluminium .01 cm. thick over the layer of active material to cut off all the α rays. Then measure the ionization current due to the β rays alone. With the aluminium sheet still covering the radium apply a fairly strong magnetic field and measure the ionization current. Observe that under the influence of the magnetic field it is reduced. Increase the strength of the magnetic field and again measure the current between P and P' and note a further reduction of the current. If the field is made sufficiently strong it should be possible to reduce the current almost to zero if not entirely so.

These experiments indicate that the β rays are deflected by the magnetic field, so that they strike the plates BB before they escape from between them, and consequently do not reach the space between P and P'. A weak magnetic field does not deflect them sufficiently, and therefore some of the rays escape beyond the plates BB, but the stronger the field the fewer the number that escape.

This deflection of the β rays points to the conclusion that the rays carry an electric charge. It is of importance to determine whether this charge is positive or negative. This may be easily determined in the following manner: Place a small quantity of radium bromide at the bottom of a narrow groove between two thick lead plates DD, as shown in Fig. 52, and cover it with the aluminium foil to cut off the α rays. This groove should be about 3 cm. deep, 1 mm. in width and 1 cm. in length so as to obtain a narrow and sharply defined beam of rays. About 6 cm. above the groove place horizontally a small photographic plate C, film side downwards. This plate should not be more than 2 cm. square. Adjust this plate so that a definite marked point on it is vertically above the groove. Place the poles of an electromagnet to cover the dotted area NN so that the field may be perpendicular to the plane of the paper. This apparatus should either be placed in a perfectly dark room or the photographic plate and groove covered

with an opaque metal tube to exclude all light to prevent the
plate C becoming fogged.   Before applying the magnetic field
allow the beam of rays to act on the plate for about thirty
minutes.   Then apply a magnetic field of about 300 or 400
units per square centimeter in a known
direction and allow the rays to act
again for about thirty minutes.   Re-
move the plate and develop it in the
ordinary way, marking, before removal,
the exact position it occupied relatively
to the rest of the apparatus.   When de-
veloped there should be two dark bands
on the plate, one of which is due to the
action of the rays before deflection and
the other due to the action after de-

FIG. 52.

flection.   The position of the latter with regard to the former
will show the direction in which the rays were deflected.   This
direction should be the same as the direction in which a stream
of cathode rays would be deflected under the action of the same
field.   This shows that the charge carried by the β rays must
be a negative charge.

93. **Magnetic Deflection of α Rays.**—One way in which the
α rays were early distinguished from the β rays was that the
latter were easily deviated by a magnetic field while the former
were apparently unaffected by such a field.   The true nature of
the α rays was not known for some time after the nature of the
β rays had been determined.   It was finally suggested as a
result of some indirect experimental evidence that the α rays
were positively charged particles emitted with great velocity.
To test the truth of this suggestion the crucial experiment, of
course, was to try to bend the rays by a magnetic field.   The
first one to succeed in doing this was Rutherford, who used the
following method : The apparatus necessary for the experiment
is shown in Fig. 53.   Place a gold leaf electroscope A of the
usual form, of about 10 cm. square, on a heavy lead plate BB,
in which an opening ab is cut.   This opening should be cov-
ered by a very thin sheet of aluminium foil not more than .0003
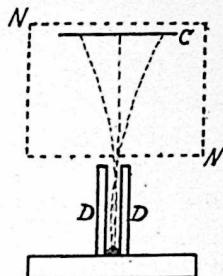
cm. in thickness.   Below this is a set of twenty-five parallel
brass plates *SS,* whose planes are perpendicular to the plane of
the paper.   Make these plates 1 mm. thick, 3.5 cm. in height
and 1 cm. in width.   They should be equally spaced apart at
a distance of .05 cm.   This is done by cutting grooves equal
distances apart in two side plates as in *C* and *D,* into which
the brass plates are slipped.   In the vessel below these
plates place a layer of strongly active radium bromide.   The
rays from the radium bromide pass up through the slits be-
tween the plates and ionize the gas in the electroscope.   The
emanation arising from the radium must be removed or else it
will produce ionization in the electroscope and mask the real
effect to be observed.   This may be done by passing a con-
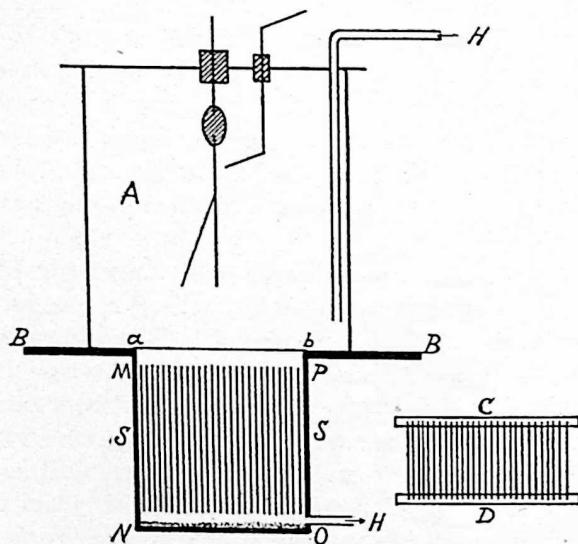
FIG. 53.

tinuous stream of dry hydrogen downwards through the elec-
troscope and the porous aluminium foil and then through the
outlet *H.*   The use of hydrogen instead of air has a great
advantage owing to the fact that the α rays are absorbed to a
much less extent in hydrogen than in air, and therefore they

are able when they reach the electroscope to produce greater effects than if they had passed through air. Hydrogen is preferable also because the effect of the β and γ rays in the electroscope is less in hydrogen than in air.

Place the part of the apparatus *MNOP* between the poles of as powerful an electromagnet as is available so that the magnetic field is parallel to the plane of the plates, that is, perpendicular to the plane of the paper in the diagram. The strength of this field should be at least 8000 units and greater if possible. Set the stream of hydrogen flowing steadily and perform the following experiments: (1) Measure the ionization in *A*, when no magnetic field is acting, by observing the rate of discharge of the gold leaf system in the usual manner. (2) Cover the radium with a sheet of aluminium or mica .01 cm. thick to absorb all the α rays, and then measure the rate of discharge of the electroscope. The first observation gives the rate of discharge due to all three types of rays, namely, the α, β and γ rays, and the second observation gives the rate of discharge due to the β and γ rays alone. Therefore the difference shows the effect due to the α rays alone. The α rays will be found to produce by far the greater amount of ionization, that due to the β and γ rays being only a small fraction of the total. (3) Remove the sheet of aluminium or mica covering the radium and apply the magnetic field and observe the rate of discharge in the electroscope and note that it is much less than in observation (1), the decrease being very much more than would be due to the cutting off of the β rays by deflection and therefore must be due to the cutting off of a large proportion of the α rays as well. (4) This may be shown by making another observation. Cover the radium again with aluminium sheet to absorb the α rays and apply the magnetic field and observe the rate of discharge and note that it is slightly less than in observation (2). The difference between (2) and (4) indicates the cutting off of the β rays by the field. This decrease is much less than the total difference between (1) and (3), showing that a large part of the difference between (1) and (3) is due to the deviation of the

α rays by the magnetic field. If the strength of field can be increased the difference between the rates of discharge in (1) and (3) may be increased, showing that the stronger the field the more rays are deflected.

These experiments show that the α rays can be deflected by a magnetic field, but it requires a very powerful field to produce appreciable deflections, and it is for this reason that the α rays were so long considered non-deviable. This deviability of the rays indicates that they carry an electric charge, and as in the case of the β rays it is of importance to determine the sign of this charge. This may be done in the following manner: Arrange another set of plates with slits between them similar to those used in the last experiments, only make the spaces between the plates 1 mm. each instead of 0.5 mm. In a brass plate about 1 mm. thick cut slits exactly the same width and exactly corresponding to the slits between the parallel plates and place this plate over the vertical plates and slits so that the brass plate covers a little over the half of the slits between the plates as shown on an enlarged scale in Fig. 54. If the magnetic field is not quite strong enough to deviate all the α rays, then if the deviation is in the direction from A to B more rays will escape through the slits than if the deviation is in the direction B to A. Apply the magnetic field first in one direction and then in the opposite one and observe the rate of discharge in each case. This will show whether the rays are bent from A to B or from B to A when the field is applied in a given direction. Observe this carefully and note that the α rays are bent in the opposite direction to that in which the β rays would be bent by the same field. Since the β rays are negatively charged the α rays must therefore be positively charged.

FIG. 54.

94. **Electrostatic Deflection of the Rays.**—Since the magnetic deflection of the β rays indicates that they carry a negative charge, it should be possible to deflect them also by means
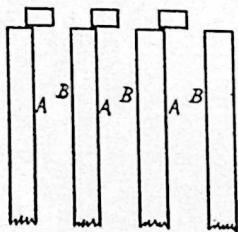
of an electrostatic field. This electrostatic deflection may be observed by the photographic method similar to that used in the case of the magnetic deflection (§ 92). Place the radium bromide in the groove formed by the two lead plates (Fig. 52) to obtain a narrow beam of rays. Cut off the α rays by covering the radium with the usual sheet of aluminium. Between the photographic place C and the groove place two metal plates parallel to each other and to the plane of the groove containing the radium. These plates should be about 4 cm. high and 2 cm. wide and 1 cm. apart.

Before applying the electric field allow the β rays to fall upon the photographic plate for about thirty minutes to indicate the undeflected direction of the rays. Then establish a difference of potential of several hundred volts between the plates and allow the rays to fall upon the photographic plate for the same time. Then develop the plate and observe that the impression produced by the deflected beam is towards the positive plate. As in the case of the magnetic deflection this indicates that the rays carry a negative charge.

The α rays may also be deflected by an electrostatic field, using an arrangement similar to that used for the magnetic deflection (§ 93), but in this case the parallel plates forming the slits (Fig. 53) must be held by ebonite side pieces C and D instead of metal to insulate them. Alternate plates should be connected together and a large difference of potential established between the two sets. This experiment is somewhat difficult to carry out, for it requires a very intense electric field to produce an appreciable deflection and the potential sufficient to produce a large deviation will cause a spark to pass between the plates which are so close together. Another method by which much greater effects are produced will be described in a later chapter (§ 110). The results of the electrostatic deflection of the α rays point to the same conclusion as the magnetic deflection does, namely, that the α rays carry a positive charge.

The γ rays differ from both the α and β rays in this matter of deviation. As yet no deflection whatever by either a mag-

netic or an electric field has been observed in the case of the γ rays. They do not appear to carry any charge, as far as is at present known.

95. Conclusions.—We may conclude then from the results of these experiments that there are three definite and distinct types of rays emitted by radio-active substances. The α rays are very easily absorbed on passing through solids and they are positively charged particles moving with a high velocity. This high velocity is indicated by the fact of the very intense magnetic or electrostatic field required to deflect them. The β rays are very much more penetrating than the α rays and they are negatively charged particles emitted with comparatively high velocity. The third type, or γ rays, are extremely penetrating, requiring large thicknesses of solids to absorb them. No indications that they possess an electric charge has ever been observed. The four radio-active substances uranium, thorium, radium and actinium under normal conditions give out all three types of rays. Polonium however gives out only α rays.

CHAPTER X.

GENERAL PROPERTIES OF RADIATIONS.

96. Methods of Differentiation.—To thoroughly investigate these rays and to differentiate one type from another there are different methods of attack. There are in general five distinct properties, some of which we have already observed, which furnish tests that may be applied to distinguish the different rays from one another as follows: (1) Their penetrability or power of passing through different substances; (2) the ease with which they may be deviated by a magnetic or electric field; (3) their power of ionizing gases; (4) their power of affecting a photographic plate; (5) their power of producing phosphorescence.

These properties are not all possessed by the different kinds of rays, but the presence or absence of them or the degree to which they are present furnish tests by which the rays may be detected and differentiated. In general the rays which produce the greatest photographic action produce the least ionization. Also the more penetrating the rays the less efficient are they as ionizers. It is very difficult to make definite quantitative measurements on the relative intensity of the three types of rays, whether we use their ionizing power, their action on a photographic plate or their prosphorescent action. For in each of these methods the proportion of the rays absorbed and transformed into the energy of ionization, or photographic or phosphorescent energy is different for each type of rays in each case, and only a portion of the energy is transformed into the form of energy used to detect the rays.

Another difficulty arises from the fact that the three types of rays are usually emitted simultaneously and it is difficult to isolate one type from the others. In most cases however fairly approximate determinations can be made.

97. Comparison of Ionization Produced by α, β and γ Rays.

—The α rays are much more efficient ionizers than either the β or γ rays. When all three types of rays are acting simultaneously on a gas by far the greater part of the ionization is due to the α rays. The γ rays are much less powerful ionizers than the β rays. A very approximate idea of the relative ionizing powers of these rays may be obtained by the following method: In a lead block not more than 6 cm. long cut a rectangular groove about 4 cm. long, 0.5 cm. wide and 2 cm. deep. In the bottom of this place a thin layer of radium bromide. About 0.5 cm. above this groove and parallel to it place two parallel metal plates in a vertical plane about 2 cm. apart. These plates should be about 6 cm. high and 5 cm. wide. Pass a slow steady stream of air over the top of this groove to prevent the emanation from diffusing upward between the plates. Place the lead block containing the radium between the poles of a fairly powerful electromagnet so that the field is parallel to the length of the groove. Apply a magnetic field sufficient to bend the β rays away, so that they may not reach the space between the plates, but not strong enough to affect the α rays. This will allow only the α and γ rays to ionize the gas between the plates. Measure the saturation ionization current thus produced by the α and γ rays. The effect of the latter is practically inappreciable compared with the former. Now remove the magnetic field and cover the radium with a sheet of aluminium about .01 cm. thick to cut off all the α rays. The β and γ rays will now ionize the gas. Measure the saturation current under these conditions. The greater part of this ionization current is due to the β rays. Now cover the radium with a thin sheet of lead about 2 mm. thick to cut off all the α and β rays. Then measure the ionization current which will be due entirely to the γ rays and will be very small, so much so that the electrometer will require to be very sensitive to detect it. The difference between the current in the last case and that in the second will give the current due to the β rays alone, while the difference between the last and the first will give the current produced by the α rays alone. The relative amount of ionization produced by the

three types of rays under the same conditions may thus be compared. It will be seen that the α rays produce several thousand times as much ionization as the γ rays, while the β rays produce ionization of the order of about one hundred times that of the γ rays.

If similar experiments are made, using the other radio-active substances such as thorium or uranium, it will be found that the relative ionizing power of the three types of rays are in the same order as in the case of radium. It will be observed also that the β rays emitted by either thorium or uranium are very weak ionizers.

By modifying the apparatus slightly the relative ionization of the different types of rays may be compared in different gases. An arrangement suitable for this is shown in Fig. 55. A is the lead block with the groove B cut in it as before. The plates P and P between which the ionization is to be measured are contained in a brass tube MN about 10 cm. high and 6 cm. diameter. These plates are supported by stout rods passing out through ebonite insulators as shown. This enclosing tube should be

Fig. 55.

made to fit closely on the flat surface of the lead block and the joints made air-tight by waxing. For these experiments use a sample of an active uranium salt as uranium emits no emanation while the other active substances do.

Place the uranium in the groove and then carefully wax down the tube MN and place the lead block between the poles of the electromagnet as before. Start with the vessel filled with air at atmospheric pressure, and, after bending the β rays out of the way by the magnetic field, measure the ionization produced by the α rays. Exhaust the vessel and fill with other gases in turn and measure the ionization current due to the α rays in each case. Now remove the magnetic field and also remove the vessel MN and cover the groove with the aluminium sheet to cut off the α rays and replace the vessel and rewax
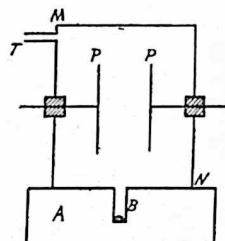
the joint. Measure now the ionization produced by the β rays in the same gases as were used in the case of the α rays. Make a careful comparison in each case and it will be found that the numbers representing the relative saturation currents produced in the different gases by the α rays are not in exactly the same ratio as those representing the currents produced by the β rays, although they follow in the same general order.

If the uranium is covered by a thin sheet of lead to cut off both the α and β rays it will be found that the ionization produced by the γ rays is very small in the various gases, and unless the electrometer is a very sensitive one they will have to be measured by means of an electroscope.

98. **Photographic Action of the Rays.**—Although the α rays are much more active as ionizers than the β or γ rays, when we come to study the action of the different types of rays on a photographic plate it is found that the β rays are much more active photographically than either the α or γ rays. The γ rays are also much less active photographically than even the α rays, and in the case of the very weak γ radiation from uranium and thorium practically no photographic effect has been found. In making experimental determinations on these radiations this difference between the ionizing and photographic properties of the α and β rays especially must be carefully taken into account, for otherwise contradictory results are very apt to be obtained. Take as an instance a case when only one kind of rays are being used, such as the α rays, for instance. If the ionization, or electrical, method of measurement is used quite a large effect may be observed from the active body, while if the photographic method of measurement is employed the effect may be very small or may even not be detected at all. If however the β rays emitted by the active body had been used just the reverse would have been observed, for the photographic action would be comparatively strong, while the ionization effect would be comparatively weak.

It is somewhat difficult to accurately compare the relative photographic action produced by the different types of rays, for in many cases the photographic plate must be wrapped in

black paper to cut off the phosphorescent light which is also given out by some of the radio-active bodies, and this paper will absorb the α rays much more than it will the β or γ rays. Then in the case of uranium or thorium where the radiations are comparatively weak it requires generally about a day's exposure to produce an appreciable effect on the plate, and during this time other effects from extraneous sources are apt to occur unless very special precautions are taken. A very approximate comparison may be made by the following method: Place a specimen of radium bromide in the groove of a lead block similar to the one shown in Fig. 55. Wrap a photographic plate about 7 cm. square in a sheet of black paper to protect it from any light and place it horizontally, film downwards, about 3 or 4 cm. above the lead block. The experiment should be done in a dark room. Bend the β rays out of the way in the usual manner and allow the α rays to fall upon the plate for about an hour or more. Now cover the radium with the usual absorbing sheet of aluminium to absorb the α rays and remove the magnetic field. Move the photographic plate so that another portion of it is above the groove and exposed to the rays. Allow the β rays to fall upon the plate for the same length of time as in the first instance. Again cover the radium with the usual absorbing lead sheet to absorb the α and β rays and shift the plate again so as to expose another portion to the γ rays. Allow the γ rays alone to act for the same time as in the other cases. Remove the plate and develop it and compare the three impressions made by the three types of rays. This experiment might be repeated for shorter times as well as longer times of exposure.

The experiments should be repeated using samples of uranium and of thorium. The time of exposure with these substances will require to be very much longer to obtain any appreciable effect. It will require about a day's exposure in each case. It will be found also that the γ rays from uranium and thorium produce practically no effect.

99. Phosphorescent Action of the Rays.—The rays emitted by the different radio-active bodies cause certain substances

to phosphoresce when the rays fall upon them.   This effect may be observed in the case of quite a large number of substances such as crystals of zinc sulphide, platino-cyanide of barium, diamond, lithium, willemite, kunzite, etc.   The various substances which show this effect are not equally affected by the three types of rays.   For instance, zinc sulphide is especially sensitive to the action of the α rays, while the platino-cyanides of barium or lithium show the effect of the γ rays to a marked degree.   These phosphorescent effects are in some cases very brilliant, and they serve as a very convenient means of detecting and observing these radiations.

In the case of some of the phosphorescent bodies there is a marked phenomenon shown by the α rays which is not shown by the β or γ rays.   When the α rays fall upon zinc sulphide, for instance, it is brilliantly illuminated, and if it be examined with a magnifying glass the illumination is found not to be uniformly distributed, but to consist of bright scintillating points as though the zinc sulphide were being bombarded and a bright scintillation resulted from each impact.   The illumination produced by the β or γ rays differs from this in being uniform and continuous, and does not show these peculiar scintillations.   This scintillating action is shown by the α rays emitted by practically all the radio-active bodies.   The phenomenon is most marked with zinc sulphide, but it may also be observed with willemite and the platino-cyanide of potassium.

On a sheet of thick white paper or very thin white cardboard dust a uniform layer of finely powdered crystalline zinc sulphide.   The cardboard should first be coated with a thin coating of paste to cause the sulphide crystals to adhere.   In a dark room place the screen horizontally about 2 cm. above a specimen of radium.   The screen should appear brilliantly illuminated.   Examine this illumination carefully with a magnifying glass and observe the bright flashes or scintillations.   Cover the radium with the usual absorbing sheet of aluminium to cut off all the α rays.   Note that the illumination diminishes in intensity and not only that but no scintillations are visible, showing that a large part of the total illumination is due to the

α rays and also that the scintillating action must be due to the action of the α rays.

If the β rays be also cut off by an absorbing metal sheet the phosphorescence produced by the γ rays alone may be observed. This action will be found weaker than that of either the α or β rays. A screen made of crystalline platino-cyanide of barium or lithium is much more suitable for showing the phosphorescent action of the γ rays than the other phosphorescent substances.

100. **Complexity of α and β Rays from Radium.**—When a narrow beam of β rays from radium is allowed to fall upon a photographic plate or a phosphorescent screen a narrow dark or bright band is produced. If a magnetic field be applied to the beam of rays it will not only be deviated as shown by the movement of the band on the photographic plate or phosphorescent screen, but the band will also be increased in width, showing that some of the rays in the beam must have been bent more than others. This indicates that the β rays from radium are not perfectly homogeneous. Some of them are projected with greater velocity than others and those with the higher velocity will of course be deviated less by a given magnetic field. The β rays emitted by uranium do not show this broadening, indicating that the beam of β rays from uranium is homogeneous in character, the rays all being emitted with the same velocity.

The α rays from radium also show a similar want of homogeneity. It is not so easily observed in the case of α rays on account of the difficulty in bending them. Careful experiments show that the α rays emitted by radium are not all projected with the same velocity.

101. **Absorption of the Rays by Solids.**—We have seen (§ 90) that one of the most marked distinguishing characteristics of the three types of rays is their different powers of penetrating solid bodies. Some further experiments on this question may prove of value. Uranium will be found a more convenient source of α and β rays for the study of this question than radium on account of the complexity of both the

α and β rays from radium, but radium is better as a source of
γ rays as it gives out a much more intense γ radiation than
uranium.

α Rays.—The form of apparatus shown in Fig. 50 will be
found convenient for the examination of the absorption of the
α and β rays. If a very thin layer of uranium be used prac-
tically all the ionization produced is due to the α rays, only
about one or two per cent. of the total ionization being due to
the β and γ rays. Place a very thin layer of uranium oxide of
about 25 sq. cm. in area on the plate C (Fig. 50) and adjust the
distance between the plates to about 2 cm. Measure the satu-
ration ionization current between the plates. Place a thin sheet
of aluminium foil, not more than .0003 cm. thick, over the
uranium and measure the current. Repeat this, adding a sheet
at a time, till all the α rays are completely cut off. Repeat
this using very thin sheets of tissue paper.

The α rays of radium may be separated from the β rays
temporarily by dissolving a little radium chloride in water and
then evaporating it on a metal plate. The radium chloride left
on the plate is thus rendered nearly free from β rays for a
short time. Using such a deposit as a source of radiation,
repeat the experiments with the aluminium foil.

If I_0 is the intensity of the rays before passing through any
absorbing material and I the intensity after passing through a
thickness x of the absorbing substance, it will be found that
the relation between I_0 and I obeys approximately the same
law as found for Röntgen rays (§ 61) under similar conditions,
namely, $I/I_0 = \epsilon^{\lambda x}$, where λ is the coefficient of absorption.

β Rays.—To investigate the absorption of the β rays use a
comparatively thick layer of uranium oxide several millimeters
thick. Cover this with a sufficient thickness of aluminium foil
to cut off all the α rays. Perform a set of experiments similar
to those made with the α rays. In this instance, however, since
the β rays are so much more penetrating, a great thickness of
absorbing material may be used and therefore a much greater
variety of substances may be tested. Test as before the rela-
tion between the absorption and the thickness of the absorbing

material and note that the absorption law given above is approximately adhered to in the case of the β rays as well as the α rays. Compare also the absorbing power of equal thicknesses of different materials and observe that the absorption increases with the density, but they are not proportional to one another.

γ *Rays.*—The absorption of the γ rays may be most successfully examined by using a layer of radium a millimeter or so in thickness as the source of rays, and an electroscope for measuring the intensity of the rays.

Place a layer of radium bromide in a shallow receptacle of not more than 1 or 2 mm. depth and 10 or 12 sq. cm. area. Cover it with a thin sheet of mica about .01 cm. in thickness and carefully seal down the edges with wax to prevent the emanation from escaping. Place an electroscope of the usual form (Fig. 14) on a lead plate in which is cut an opening about 6 cm. square. About 2 or 3 cm. below this opening place the enclosed radium and cover it with a sheet of lead about 2 or 3 mm. thick so as to completely cut off the β rays. Measure the intensity of the γ rays by the rate of discharge of the electroscope. Then cover the radium with gradually increasing thicknesses of absorbing materials and note the diminution in intensity with increase of thickness for each substance. Test this by the absorption equation given above. Compare also the absorbing powers of different substances for γ rays. It will be found that the thicknesses of absorbing materials required in these experiments to produce appreciable absorption are very much greater than in the experiments with α and β rays. Quite appreciable effects will be produced by the γ rays even after they have passed through several centimeters of such a dense substance as lead. In all these experiments on absorption it will be found instructive to plot curves showing the relation between the intensity of the rays after passing through the absorbing material and the thickness of the absorbing substance.

102. Effect of Varying the Thickness of a Layer of Radio-active Material.—In some of our experiments we have used

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as our source of radiation a thin layer of radio-active material
and in others a thick layer. The reason for this will now be
apparent after studying the absorptive power of solid bodies
for these radiations. The radiations are emitted from all parts
of the radio-active material, not only at the surface but through-
out the body of the substance. If there were no such thing
as absorption then the rays from all parts of the material
would emerge into the air with equal intensity and produce
their effects and any increase in the quantity of material would
produce a proportional increase in the amount of radiation
emitted. But since absorption does take place, when the layer
of material is thick then the rays which are given off from the
lower layers have to pass through the upper layer before emerg-
ing into the air and therefore suffer absorption in passing
through the solid material, whereas if the layer is very thin
practically no absorption takes place, as the distance traversed
is so very short. On account of the difference in the penetrat-
ing powers of the three types of rays the effect of altering the
thickness of the radiating material is different in the three
cases. Consider the effect on each type of ray separately.

Effect on α Rays.—The α rays given off from a very thin
layer suffer no absorption as they are all practically given off
from the surface and the full effect of the rays is observed in
the air above the material. If the layer of material is appre-
ciably increased the amount of radiation emitted is increased in
the same proportion, but the rays emitted from the lower layer
have to pass through the increased thickness of material and on
account of their weak penetration suffer absorption and only a
portion of them finally emerge into the air. Therefore the in-
crease in the emergent radiation is not proportional to the
increase in thickness. The thicker the layer the more are the
α rays from below absorbed, until finally a thickness is reached
which is sufficient to completely absorb all the α rays which
come from a depth below this thickness. Consequently when
this condition is reached any further increase in the thickness
of the material will produce no further increase in the emer-
gent α radiation. Starting, therefore, with a very thin layer of

material the ionization will increase with increase in thickness until a maximum is reached at the point where the thickness is sufficient to absorb all the α rays coming from below this depth and the maximum will remain constant for any increase in material.

β *Rays.*—The effect is very much less marked in the case of the β rays. The latter are so much more penetrating than the α rays that they will pass through a much greater thickness of radio-active material without suffering much absorption. If the ionization produced by the β rays from a thin layer is measured and the thickness of material gradually increased the ionization will increase much more nearly in proportion to the amount of material, for the β rays from the lower layers are absorbed to such a small extent that covering the lower layer with more radio-active material does not produce much absorption. Finally, of course, a thickness will be reached which will absorb all the β rays emitted from below this thickness but the quantity of material will be very much greater than that required to absorb the α rays.

γ *Rays.*—The γ rays are so extremely penetrating that they will pass through a very large quantity of radio-active material before being absorbed to any appreciable extent. The ionization produced by the γ rays alone will therefore be practically proportional to the quantity of radio-active material used. To obtain an intense γ radiation a large quantity of material may be employed.

Experimental Tests.—The results given above may be very easily observed experimentally. Use the apparatus shown in Fig. 50 and as a receptacle for holding the radio-active material use the one described in § 85, so as to use the same surface area in all cases. The detachable plate with the hole in it should be about 1 cm. thick to give sufficient depth and the hole in the plate should be about 5 cm. square. Place as thin a layer as possible of uranium oxide on the bottom of the receptacle. This may be done by sifting the oxide through a thin wire gauze as uniformly as possible. Measure the current between the plates. Weigh the plate before the oxide is

placed on it and also afterwards to obtain the weight of oxide. Increase the thickness of oxide slightly and again measure the current and weigh the oxide. Continue this until the current approaches a maximum. If the material is uniformly sifted over the area the thickness may be taken as proportional to the weight in each case. Plot a curve showing the relation between the thickness and the current produced. With the thicker layers the β rays become more prominent and part of the current is due to them.

Start again with a thin layer and cover it with a sheet of aluminium thick enough to absorb all the α rays. Repeat the above experiments and observe the relation between the thickness of material and the ionization produced by the β rays.

The quantity of α rays emitted by uranium oxide is very small and besides that the γ rays are very weak ionizers. Consequently the γ radiation from a very thin layer of uranium is practically inappreciable and considerable thickness is required to produce much effect. Start with a layer a couple of millimeters thick and cover it with a lead plate about two millimeters in thickness to absorb all the α and β rays. Repeat the above experiments and compare the ionization produced by different thicknesses of material. To measure the ionization use the usual form of electroscope.

Test also the γ radiation from specimens of thorium and of radium. In these tests the emanation will not interfere, as the thorium or radium may for this purpose be covered with a sheet of mica and sealed up so as to be air-tight. Note that it requires a considerable thickness of thorium to produce appreciable ionization by the γ rays, but that a much thinner layer of radium will produce as great if not greater effects.

103. Absorption of Rays by Gases.—The rays from radioactive substances suffer absorption in their passage through gases as well as through solids, but of course to a much less extent. The γ rays are so penetrating that the absorption of them by gases is extremely small. The β rays will pass through a considerable distance without showing much diminution in intensity but the distance is much less than in the case of γ rays.

The α rays, on account of their low penetrating power, are comparatively easily absorbed by gases. This absorption of the α rays by gases may be easily observed by means of the apparatus shown in Fig. 56.

AB is a brass plate 12 cm. square supported in a fixed position by a brass rod *R* passing out through an ebonite plug. Parallel to *AB* and attached to it by ebonite rods is the plate *CD* of the same size in which is cut an opening about 8 cm. square. This opening is covered with extremely thin aluminium foil or very thin wire gauze. The distance between these plates should be about 1.5 cm. *AB* is connected to the electrom-
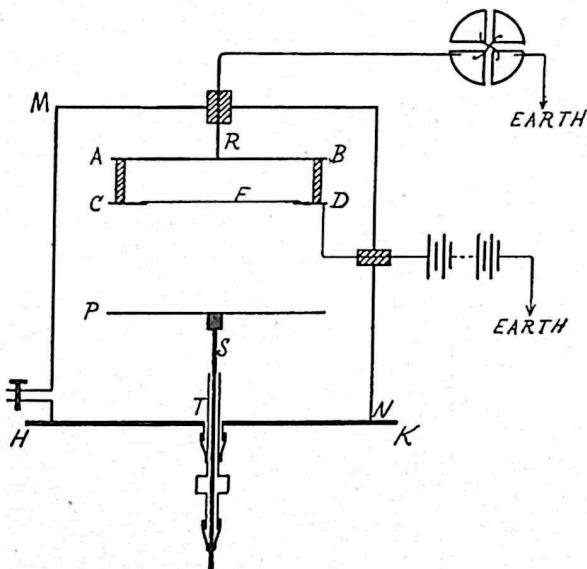
FIG. 56.

eter and *CD* to a battery in the usual manner. A plate *P* about 14 cm. square is supported by a rod *S*, which passes through a closely fitting tube and nut attached to the base plate *HK*. By means of this nut *P* may be raised or lowered parallel to itself so the distance between *P* and *CD* may be altered as desired. A piece of rubber tubing fits tightly over the lower

part of this nut and the rod S so as to make the joint air-tight. The whole system of plates is enclosed in a metal box MN which fits on to the base plate HK. The joints may all be made air-tight by waxing. There should be a couple of windows in the sides of the vessel to observe the interior. The radio-active material is placed in a uniform layer on the plate P covering an area of 12 cm. square. Connect the plate P and the enclosing vessel to earth. The rays from the radio-active material on P ionize the fixed volume of gas between the plates AB and CD between which the current is measured. Since the rays are absorbed in passing through the gas between P and CD we should expect the current between AB and CD to diminish as the distance between P and CD is increased. Place a thin layer of uranium oxide on P so that practically all the ionization is produced by the α rays and the β rays may be neglected. Start with P a couple of millimeters or so from CD and measure the current, then gradually lower the plate P by small measured intervals and measure the current at each distance and observe how the current diminishes with increase of distance. Plot a curve showing the relation between current and distance between P and CD. It will be seen that as the distance increases in arithmetical progression the current diminishes approximately in geometrical progression.

As was shown in § 101 for solids if I_0 is the intensity of the α rays at the surface of the radio-active material and I the intensity at a distance x from it then $I = I_0 \epsilon^{-\lambda x}$, where λ is the coefficient of absorption for the gas. Let x be the distance between P and CD and l the distance between CD and AB. The rays are also absorbed in passing through the foil F by a small constant fraction. Let the fraction which emerges after passing through the foil be denoted by K. Then the intensity of the rays at the upper surface of F is equal to $KI_0 \epsilon^{-\lambda x}$ and at the lower surface of AB it is $KI_0 \epsilon^{-\lambda(x+l)}$. Then since the amount of ionization produced is proportional to the intensity of the rays the number of ions produced between the plates is proportional to $KI_0 \epsilon^{-\lambda x} - KI_0 \epsilon^{-\lambda(x+l)}$, that is to $KI_0(1 - \epsilon^{-\lambda l})\epsilon^{-\lambda x}$. Therefore since $KI_0(1 - \epsilon^{-\lambda l})$ is constant

for given conditions the saturation current between the plates is proportional to $\epsilon^{-\lambda x}$, that is it decreases according to an exponential law with the increase of distance from the source as was observed by experiment.

Fill the vessel with other gases in turn and repeat the experiments and plot the corresponding curves, using distances between CD and P as abscissæ and currents as ordinates.

Since the current C is proportional to $\epsilon^{-\lambda x}$ and also proportional to the deflection d of the electrometer needle, then d is proportional to $\epsilon^{-\lambda x}$. By observing d_1 and d_2 for two known distances x_1 and x_2 in any gas and supplying these values in the equation $d_1/d_2 = \epsilon^{-\lambda x_1}/\epsilon^{-\lambda x_2}$ the value of the coefficient of absorption λ may be determined for this gas. Calculate from the observations the value of λ in each gas.

By more elaborate and careful measurements it has been found that the relative ionization in gases is proportional to the relative absorption. The ionization produced by the rapidly moving α particles is due to their collisions with the molecules of the gas. The more collisions that take place the more ions will be produced. It requires energy to produce these ions, and the energy is derived from the kinetic energy of the α particles. The energy of the α particles is thus gradually reduced in their passage through the gases, and if their energy is reduced below a certain amount they do not possess sufficient energy to produce ions and therefore lose their power of manifesting their presence. The energy of the rays is thus absorbed and there is therefore a direct relation between the amount of absorption and the amount of ionization in any given gas.

This method is not a convenient one to measure the absorption of either the β or γ rays by gases, for on account of their much greater penetrating power it would require a great distance between the plates P and CD to produce an appreciable absorption which could be measured with accuracy. If greater distances were used to produce sufficient absorption to be measured the rays would spread out to such an extent that the intensity of radiation could not be considered constant over a plane parallel to the plate P at a great distance from P.

Using the same apparatus repeat these experiments for each of the gases at different pressures below an atmosphere. Observe that for any given gas the absorption is very approximately proportional to the pressure of the gas as would be expected.

104. Effect of Pressure on Ionization.—The rate at which ions are produced by the radiations from radio-active bodies depends upon the pressure of the gas. In the study of Röntgen rays (§ 62) it was seen that the saturation current between two parallel plates was proportional to the pressure. In this instance the ionization between the plates was practically uniform. The same is true for the ionization produced by the rays from radio-active substances if the ionization between the plates is uniform. If a radio-active body giving out α rays be placed on the plate C (Fig. 50) which is placed at a distance of 4 cm. from D and the current measured in air at atmospheric pressure and also at gradually decreasing pressure below an atmosphere the current will be found to decrease as the pressure decreases, but at first the decrease of current will be less rapid than the decrease of pressure until a pressure of about half an atmosphere is reached. For pressures below this the current will decrease in exact proportion to the pressure. If the vessel be filled with carbon dioxide in place of air the want of proportionality will continue till the pressure is in the neighborhood of about one third of an atmosphere and below that the current will be proportional to the pressure. These results appear at first sight to be contrary to the statement that the ionization is proportional to the pressure, but in reality they follow as a natural consequence of the absorption of the rays by the gas. Since the α rays which produce the greater part of the ionization are so very easily absorbed by the gas the intensity of the rays is greatest at the surface of the plate C and gradually diminishes towards D. The ionization is therefore not uniform between the plates, as more ions are produced near C than near D. As the pressure is decreased the absorption is less and at first the rays are able to penetrate with greater intensity into the region nearer D and are therefore

able to produce more total ionization. The increased intensity therefore partly counterbalances the decreased pressure. This condition of affairs continues until such a pressure is reached at which the rays are able to penetrate to *D* with practically their full intensity, and the ionization between the plates is uniform over the whole space and remains uniform for any further decrease of pressure. From this stage then the ionization is proportional to the pressure. This phenomenon is more marked the denser the gas which is ionized. The

FIG. 57.

curves shown in Fig. 57, which are due to Rutherford, illustrate very clearly this general phenomenon in the case of three different gases. The dotted line shows where the curves would run if direct proportionality were shown over the whole range of pressure.

This effect of absorption is more marked the greater the distance between the plates *C* and *D,* for the greater the distance the rays have to travel the more absorption takes place. If the plates be placed only 5 or 6 mm. apart instead of 4 cm. the rays are absorbed to a very much less extent and the ionization between the plates is much more nearly uniform at atmospheric pressure than in the case of the greater distance. As the pressure is decreased the stage at which the ionization is quite uniform is reached much more quickly and the current is much more nearly proportional throughout the range of pressure.

These facts just described may be very easily tested experimentally by means of the apparatus shown in Fig. 56 slightly modified. Remove the lower plate *CD* and the ebonite rods and insulate the plate *P.* The latter may be done by attaching
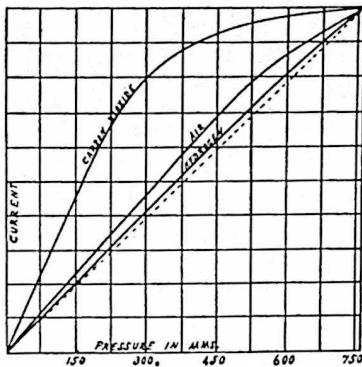
an ebonite block to the under side of P into which the rod S fits. Then connect P to the battery and use AB and P as the two plates between which the ionization occurs. Place these plates about 4 cm. apart and, using a thin layer of uranium placed on the plate P, measure the saturation current at different pressures from an atmosphere downwards. Repeat this when the plates are at shorter distances apart. Plot the curves on the same scale, showing the relation between current and pressure in each case and make comparisons. Repeat this for the different available gases.

If the β rays are used as the ionizing agent the ionization produced will be much more nearly proportional to the pressure on account of their greater penetrability.

105. Relation Between Current and Distance Between the Plates.—It was shown (§ 56), in studying Röntgen rays, that if a beam of Röntgen rays passed between two parallel plates so as to produce uniform ionization between them and the saturation current measured for different distances apart of the plates the current was proportional to the distance between them. The same is true for the α rays from radio-active bodies if the ionization is uniform. The absorption of the latter type of rays, however, produces in this connection a similar result to that described in the last paragraph. As the distance between the plates increases the absorption increases and consequently the ionization does not rise as quickly as it would if the rays could penetrate the whole distance without suffering any absorption. If there were no absorption the ionization would increase in proportion to the distance between the plates. Since the absorption is greater at higher pressures this deviation from direct proportionality is more marked at the higher pressures than at the lower ones.
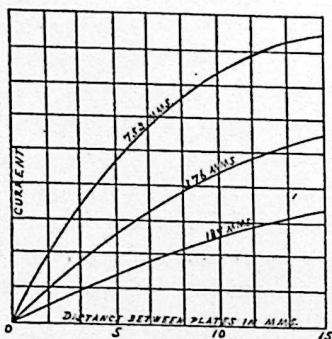
FIG. 58.

This effect is well illustrated by a set of curves, which are due to Rutherford, shown in Fig. 58. At the lower pressures the current is much more nearly proportional. to the distance than at the higher pressures. These effects may be verified experimentally by use of the same apparatus used in the experiments of the last paragraph. Keeping the pressure fixed, measure the current for different distances between the plates from 2 or 3 cm. downwards and plot a curve showing the relation between current and distance between the plates. Obtain similar curves for several different pressures. Repeat these experiments also in different gases and reducing the observations to the same scale compare them.

If the β rays are used as ionizers, since they are much more penetrating than the α rays, the absorption will play a much less important part and the current due to the β rays will be much more approximately proportional to the distance.

CHAPTER XI.

SOME SPECIAL PROPERTIES AND CONSTANTS
OF THE RAYS.

106. Electric Charge Carried by β Rays.—The magnetic and electrostatic deflection of both the α and β rays show that these rays must consist of charged particles travelling with high velocity. The direction of deflection shows in each case the sign of the charge carried. If these rays then carry a charge, and they be allowed to fall upon an insulated metal plate the plate ought to receive a charge. A practical difficulty immediately arises in trying to demonstrate this experimentally, for the gas surrounding the plate becomes ionized by the rays and conducts the charge away from the plate as fast as it is received and therefore no resultant charge remains to be observed. This difficulty may be overcome in the case of the β rays by a special method used by M. and Mme. Curie.

In this experiment a heavy metal plate AB (Fig. 59) was connected to an electrometer by a wire C. This plate and wire
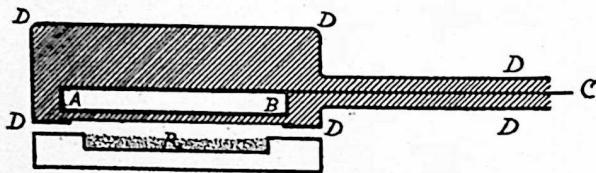
FIG. 59.

were completely surrounded by an insulating substance, either ebonite or paraffin. This prevented the air from coming in contact with the plate and discharging it. This insulation was surrounded by a metal covering connected to earth. On the lower side the insulation and metal covering were very thin to allow the rays to pass through without much absorption. The metal was aluminium foil .01 mm. thick and the ebonite

was .3 mm. thick. The radio-active material R was contained in a hollow cut in a heavy lead block. The β rays were sufficiently penetrating to pass through the covering and, falling upon the plate AB, gave up their charge to it. The electrometer indicated that AB received a negative charge. This charge was small, but could be measured by a sensitive electrometer. The charge must have been directly communicated to the plate by the rays, for no ionized gas could come in contact with the plate. From other considerations Rutherford has made a determination of the number of β particles emitted per second by one gram of radium bromide and has found it to be 4×10^{10}.

107. "Radium Clock."—A very simple and ingenious method of demonstrating experimentally that the β rays carry a negative charge has been devised by Strutt, which, on account of its periodic and automatic motions, is often called the "radium clock." Since the β rays carry a negative charge, they ought to leave the radium or the substance from which they come positively charged. When the radium is exposed to the air this fact cannot be observed, for the ionized air discharges the radium as soon as it is charged, and besides that the positively charged α particles are also emitted simultaneously with the β particles, and they would leave the radium negatively charged and thus tend to counterbalance the effect of the β rays. In Strutt's apparatus, which is shown in Fig. 60, these experimental difficulties are overcome. A sealed tube T contains some radium which is in metallic contact with two gold leaves L and L. Q is an insulating quartz rod. The tube T is

FIG. 60.

made thick enough to completely absorb all the α rays but allows the β rays to pass through, and therefore the α rays with their positive charge do not escape from the system. This whole system is enclosed in a large glass tube coated on the
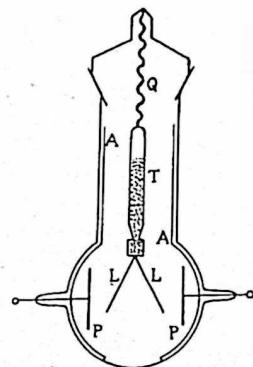
inside with tinfoil connected to earth to prevent the charging up of the case. The air is .pumped out as completely as possible to prevent conduction through the gas, so that any charge acquired by the central system may not be lost by conduction. As the β rays carrying the negative charge leave the tube the insulated system connected with the radium becomes positively charged and the gold leaves diverge. Two metal plates, P and P, connected to earth, are placed so that when the leaves reach a given distance apart they touch the plates and lose their charge and collapse, but they immediately begin to charge up again. This arrangement will work automatically at a practically constant rate, depending upon the activity of the radium, for a number of years. From other evidence which will be deduced later we have reason to believe that this rate would change after a very large number of years, due to the diminution in the number of β particles emitted.

108. Electric Charge Carried by α Rays.—The method of § 106 cannot be satisfactorily applied to the α rays on account of their very weak penetrating power. Any covering which could satisfactorily be used as a shield would absorb the α rays before they reached the plate AB.

Recently Rutherford and Geiger have devised a very novel and ingenious method for not only measuring the charge carried by the α particle, but actually counting the number of α particles emitted by radio-active bodies. The method used by them requires very careful manipulation and is attended by some experimental difficulties which have to be overcome but cannot be given in detail here. The following is the general principle of their method.

The amount of ionization produced by a single α particle is very small and would be very difficult to measure except by an exceedingly sensitive apparatus. The ionization current produced by a single α particle was magnified by a special method depending on the principle of the production of ions by collision (§ 67). The α particles were allowed to pass through a very small opening into a detecting vessel containing gas at a low pressure in which an electric field was established very

nearly equal to the value required to produce a spark. When an α particle enters this strong field the velocity of any ions produced is so increased by the powerful field that more ions are produced by collision and therefore the ionizing effect of the α particle is greatly magnified. The entrance of an α particle is therefore marked by a sudden throw of the electrometer needle due to this sudden production of ions. By careful adjustment of the electric field, etc., they were able to detect the entrance of a single particle and therefore to actually count the number entering in a given time by noting the number of throws of the needle. By this method they determined that the total number of α particles expelled per second from one gram of radium in equilibrium is 1.36×10^{11}.

In this connection they also observed by the eye the number of scintillations produced when the α particles fell upon a phosphorescent screen of zinc sulphide. The number of scintillations was found to be the same as the number of impinging α particles counted by the electrical method. So the α particles may be counted by either the electrical or scintillation method.

These experiments on the α particles mark a wonderful advance in modern experimental methods, and are especially noteworthy as this is the first instance in which a single isolated atom of matter has been independently detected and measured in any way. This is possible, of course, simply on account of the great energy possessed by the α particle. We shall see later that the α particle is really an atom of helium carrying a charge, and therefore a single atom may be isolated by this method.

During this series of experiments on the α particles the charge carried by each particle was experimentally determined. Since the number of α particles emitted per second by a known quantity of radium is known, the charge carried by each one may easily be found if the total charge carried by the known number of particles be measured. This quantity was measured and it was found that each α particle carried a positive charge of 9.3×10^{-10} electrostatic units.

109. Velocity and Value of e/m for β Rays.—The deviability of the β rays by a magnetic and an electrostatic field makes it possible to experimentally determine the velocity of these particles and the ratio of the charge to the mass by a method similar in principle to that used for the same purpose for cathode rays described in § 36. Becquerel used this principle and allowed a narrow beam of rays to fall upon a photographic plate and observed the deviation produced by known magnetic and electrostatic fields. He found the average velocity to be about 1.6×10^{10} cm. per second. The velocity of cathode rays we have seen (§ 36) is 2.8×10^9 cm. per second so the velocity of the β rays is considerably greater than that of the cathode rays.

As we have previously noted the β rays from radium are complex. This was shown in Becquerel's experiments by the fact that some of the rays are bent more than others by the same field. He found that the velocities varied from about 6×10^9 to 2.8×10^{10} cm. per second. The latter velocity approaches very nearly the velocity of light, which is 3×10^{10} cm. per second.

Using the same rays, which had a velocity of 1.6×10^{10} cm. per second, Becquerel determined the value of e/m and found it to be 10^7. This does not differ much from the value found by J. J. Thomson (§ 36) for the cathode ray particle which indicates that the β particle is similar to the cathode ray particle carrying the same charge and of about the same mass.

This complexity of the β rays with regard to velocity led Kaufmann to examine whether the value of e/m for these rays varied with the speed. He showed experimentally that the value of e/m decreased when the speed increased. If we make a most probable assumption that the charge on the β particle is constant the mass then appears to increase with the increase of velocity. It has been demonstrated from purely theoretical considerations by several mathematical physicists that the apparent mass of a moving electron is due, either wholly or in part, to the electric charge in motion, that is,

when an electric charge is in motion it appears to possess what corresponds to inertia due to the fact of its being in motion. This apparent inertia, according to this view, is not due to material mass as we are accustomed to conceive of it but is a direct result of the motion of the electric charge. These theoretical considerations further show that this apparent mass, which appears to be electrical in origin, increases with the speed of the moving charge. The experimental results of Kaufmann appear to confirm the theoretical view that the mass of the electron is due, wholly or in part, to the fact that the electric charge is in motion.

110. **Velocity and Value of** e/m **for** α **Rays.**—The determination of the velocity of projection of the α particles and the ratio of their charge to their mass is much more difficult experimentally than the corresponding determination for the β particles on account of the comparatively small deflection produced by even quite powerful electrostatic and magnetic fields and very special methods have to be used. Several determinations of these values have been made, but the most recent and accurate determinations have been made by Rutherford who used the following method.

It is important that as homogeneous and as active a source of rays as possible be used for this purpose. Radium, for reasons which will be explained later, although strongly active, gives out a complex set of α rays. Rutherford therefore used as his source of rays a very active deposit of radium C on a thin wire about 0.5 mm. in diameter. (The explanation of and method of depositing radium C will be given in Chapter XIV.) This source of rays possesses several advantages. The rays are homogeneous in character; they suffer no absorption by the active material, as the layer of active material on the wire is so extremely thin; also the source is very small and sharply defined as the deposit can be made on a very thin wire.

The apparatus used in the case of the magnetic deflection is shown in Fig. 61. The wire with the active material on it was placed in a groove V at a distance of 2 cm. below a narrow slit S. The rays passed through this slit and then fell upon

a small photographic plate P which was supported at a fixed distance of some 4 or 5 cm. above the slit. Over the whole system a brass tube T was placed from which the air could be rapidly exhausted. The removal of the air is important as it lessened the absorption of the rays which are so easily absorbed, and therefore greatly increased the intensity at the photographic plate. Besides this the diminishing of the absorption allows the plate to be placed farther from the source so that a larger movement of the photographic impression is produced. This tube and enclosed system was placed between the rectangular poles of a very powerful magnet so that the uniform magnetic field extended from a distance of 1 cm. below the slit to the top of the tube T. The magnetic field was applied for a given time in one direction and then reversed so as to deflect the rays in the opposite direction. The field was thus reversed every ten minutes for a period of about one hour. This was done so that the distance between the photographic impressions on the plate would be double of what the distance would be if the field were applied in only one direction. The strength of magnetic field used was about 9470 C.G.S. units, and this would produce a separation between the bands of 4.7 mm. when the photographic plate was 4 cm. from the slit.
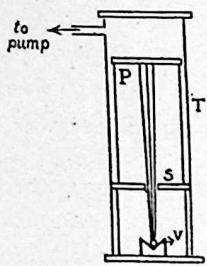
FIG. 61.

The path of the deflected beam of rays constitutes a curve whose radius of curvature may be easily calculated from the known dimensions.

Let $2r =$ the distance between the centres of the bands on the photographic plate,

$r_1 =$ the distance between the plate P and the slit S,

$r_2 =$ the distance of the slit S above the beginning of the magnetic field.

Then since the curvature is small the radius of curvature ρ is given by the equation

$$2\rho \times r = (r_1 + r_2)r_1,$$

therefore $\qquad \rho = \dfrac{r_1}{2r}(r_1 + r_2).$

It has been previously shown (§ 36) that when a charged body of mass m and carrying a charge e is in motion with a velocity v in a magnetic field of strength H the radius of curvature of the path is given by the equation $H\rho = mv/e$. The values of H and ρ are determined and therefore mv/e is known.

The apparatus used for the electrostatic deflection of the rays is shown in Fig. 62. A similar source of radiation was placed in a groove at W. Two insulated parallel plates A and B about 4 cm. high and 0.21 mm. apart formed a very narrow slit for the rays to pass through. After passing through this narrow slit the rays fell upon a photographic plate P. The whole was enclosed by the brass tube M which could be quickly ex-

FIG. 62.

hausted. The deflecting potential was applied between the plates A and B, the former being in metallic contact with the enclosing vessel while the latter was insulated from it. This deflecting potential was applied first in one direction and then in the other at intervals so that a double deflection of the rays was the result.
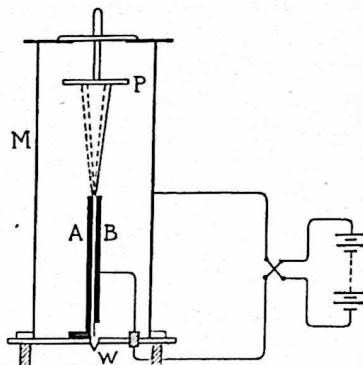
The mathematical demonstration of the theory of this experiment is somewhat lengthy and more complicated that in the case of the magnetic deflection, and consequently will not be given in detail here. If desired it may be found in the original paper* by Rutherford. If the height of AB is h_1, the distance from the top of B to the plate P is h_2, the distance between the plates is d, the distance between the extreme edges of the

* *Phil. Mag.,* Oct., 1906,

photographic bands for a reversal of the electric field is d_1 and the deflecting potential V then, from the theory under proper conditions, the following equation is true, namely,

$$\frac{mv^2}{e} = \frac{8\,Vh_2^2}{(d_1 - d)^2},$$

which gives the value of mv^2/e. Combining this value with the value of mv/e obtained from the magnetic deflection the value of v and of e/m are determined. The latest results obtained by Rutherford and other experimenters show that the value of e/m is the same for the α rays emitted by the various radio-active substances and is equal to 5×10^3 in electromagnetic units.

Although this quantity is constant the velocity of expulsion of the α particles is not the same for all substances. It is found to vary from about 1.56×10^9 to 2.25×10^9 cm. per second under different circumstances.

111. **Mass and Nature of the α Particle.**—These results along with others enable us to obtain a more definite idea of the mass of the α particle and consequently of its true nature. The value of E/M for the atom of hydrogen liberated in the electrolysis of water is in round numbers 10^4 electromagnetic units. The charge E carried by the hydrogen atom is believed to be the smallest fundamental charge carried by any existing particle of matter so that the charge carried by any body must be an integral multiple of E. The charge carried by a hydrogen ion is equal to the charge carried by a gaseous ion, which was found (§ 81) to be 3.4×10^{-10} electrostatic units. Rutherford has recently shown however that certain experimental errors in the determination of this charge carried by the gaseous ion tend to make this value too small and it is most probably in the neighborhood of about 4.6×10^{-10}. We have also seen (§ 108) that the charge carried by the α particle is equal to 9.3×10^{-10} electrostatic units. It follows then from this that the α particle carries twice the charge carried by the hydrogen atom. This being so it follows, since $E/M = 10^4$

and e/m for the α particle is equal to 5×10^3 and $e = 2E$, that the mass of the α particle must be four times the mass of the hydrogen atom and therefore must be atomic in size. Now the atomic mass of helium is 3.96 in terms of hydrogen. Thus we see that the α particle is atomic in size and of the order of the helium atom, and therefore must take its place among the elements. But since there does not seem to be any place according to the periodic law among the elements for a new one in that part of the series the most probable hypothesis is that the α particle is an atom of helium carrying twice the charge of a hydrogen atom. The α particle when its charge is neutralized becomes an ordinary uncharged helium atom. This theory is further supported by the fact that helium is very commonly found along with old radio-active minerals.

112. Energy of the α Particle.—Since the α particle is atomic in size and is travelling with high speed it must possess considerable kinetic energy. It will be of interest to calculate this energy, which may be easily done by means of the results just obtained. The kinetic energy of a mass m moving with a velocity v is equal to $\frac{1}{2}mv^2 = \frac{1}{2}m/e \cdot v^2 \cdot e$. The value of m/e is $1/(5 \times 10^3)$ electromagnetic units. The average value of v is practically 2×10^9 cm. per sec. The charge e is 9.3×10^{-10} electrostatic units which equals $\dfrac{9.3 \times 10^{-10}}{3 \times 10^{10}}$ electromagnetic units, which equals 3.1×10^{-20}. Supplying these values in the above expression we have the average kinetic energy of each moving α particle equal to

$$\frac{1}{2} \cdot \frac{1}{5 \times 10^3} \times (2 \times 10^9)^2 \times (3 \cdot 1 \times 10^{-20}) = 12 \cdot 4 \times 10^{-6} \text{ ergs.}$$

113. Nature of the γ Rays.—The γ rays differ very essentially from the α and β rays. They are, as we have seen, extremely penetrating compared with the .other two types. Very active radium bromide emits γ rays which can be detected after passing through as much as 30 cm. of iron. There is a still greater essential difference in the fact that no one has as yet succeeded in deviating the γ rays by either a magnetic or

electric field. They do not appear to carry any electric charge at all. It has consequently been very difficult to determine the real nature of the γ rays by direct experiment. Their great penetrating power and non-deviability show a strong resemblance to very hard Röntgen rays. Two rival theories as to the nature of γ rays have been put forward, each of which has a considerable amount of experimental evidence in its favor, but up to the present neither has been thoroughly established.

We know that Röntgen rays are produced by the sudden stopping of a moving electron, and it is reasonable to suppose that they would be produced by the sudden starting of an electron into rapid motion. Now experiment has shown that γ rays always occur in conjunction with rapidly moving β particles which we know are electrons. It is therefore reasonable to suppose that the γ rays are electromagnetic pulses similar to Röntgen rays produced by the sudden expulsion of the β particles, or electrons, from the radio-active substance. This theory has a large amount of evidence both of a theoretical and experimental nature to support it.

Another theory has recently been advanced by Bragg to the effect that these rays, instead of being of the nature of a vibration, are of a material nature. He suggests that they consist of neutral pairs of positively and negatively charged particles. Their neutral nature would account for the non-deviability by a magnetic or electric field. He has also deduced considerable experimental proof in favor of this theory. Although the balance of proof at present seems to be in favor of the electromagnetic pulse theory, yet neither theory has been satisfactorily proved or disproved and further experimental data are required on this subject.

CHAPTER XII.

URANIUM X, THORIUM X, ACTINIUM X.

114. Discovery of Uranium X and Thorium X.—In the year 1900 Sir William Crookes showed that by a simple chemical process he could separate from uranium a constituent which was many times more active photographically than the uranium from which it was separated. In addition, the separation of this constituent left the uranium photographically inactive. This new and unknown substance he called uranium X, or Ur. X. Becquerel obtained similar results, using a slightly different chemical process, and in addition he discovered the curious fact on testing some months later the uranium X and the uranium from which it had been separated that the uranium had completely recovered its usual amount of activity while the Ur. X had entirely lost its activity. Rutherford and Soddy later succeeded in performing a similar chemical operation on thorium, separating a very active constituent which they called thorium X, or Th. X, and which acted in a manner very similar to Ur. X. We will now study these actions a little more in detail.

115. Chemical Separation of Ur. X.—Dissolve a few grams of uranium nitrate in water and then add just sufficient ammonium carbonate to precipitate the uranium from the solution. This precipitate contains the uranium X as well as the uranium. If an excess of the ammonium carbonate be added the uranium will be redissolved, but the uranium X will not be dissolved and will be left behind as an insoluble precipitate. Separate this insoluble precipitate from the solution and dry it. Also evaporate the dissolved uranium solution to dryness. The Ur. X and uranium residue are now entirely separated.

116. Activity of Uranium and Ur. X.—Using a small testing vessel of the form shown in Fig. 50 test the uranium residue in the usual manner for α ray and β ray activity separately.

It will be found that the uranium residue has entirely lost its β ray activity but that its α ray activity is undiminished. Test in the same way the uranium X precipitate and observe that it emits no α rays at all but gives out a strong β radiation. If these two precipitates be tested photographically it will be found that the radiations from Ur. X will produce a strong impression on a photographic plate, but that the uranium residue is practically inactive photographically.

These results furnish an excellent illustration of the difference between the electrical and photographic methods of testing radio-active bodies. Tested electrically the uranium residue is quite active because it gives out only α rays which are strong ionizers, while the Ur. X is practically inactive, as it gives off only β rays, which are very weak ionizers. Tested photographically the opposite result is obtained, namely, that the uranium residue is practically inactive, because the α rays which it emits produce very little photographic effect, while the Ur. X is very active because the β rays are strongly active photographically. Great care must therefore be observed in comparing measurements made by the two different methods, to avoid confusion, for the two methods, as we see, give in some cases entirely opposite results.

117. **Change in Activity of Uranium and Ur. X.**—Starting immediately after the chemical separation of uranium and Ur. X test, by the electrical method, both substances for both α and β ray activity separately and repeat these tests at intervals of about once a day for a period of from 75 to 100 days, or even longer if time will permit. The curious fact will be observed that the α ray activity of the uranium residue will remain constant, but the β ray activity gradually increases with the time and finally reaches a maximum and then remains constant. The β ray activity may, of course, be measured separately by cutting off the α rays in the usual manner. It takes it a little over five months to reach this maximum. The β ray activity of the Ur. X, on the other hand, gradually decreases with the time, and not only so but decreases at exactly the same rate that the β ray activity of the uranium residue increases.

Plot a curve in each case showing the relation between the time and the β ray activity as measured by the ionization current. Two such curves, due to Rutherford and Soddy, representing this decay and recovery of activity are shown in Fig. 63, in which the ordinates represent the activity as measured by the ionization current, while the abscissæ represent the time· in
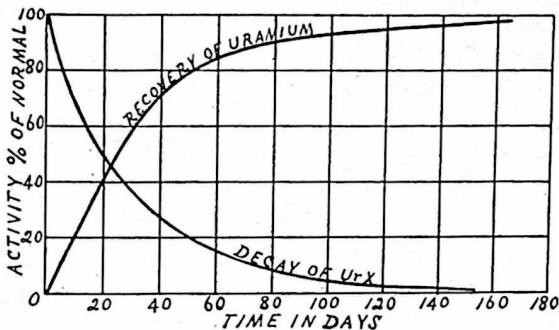
FIG. 63.

days after chemical separation. These curves represent in both cases the activity as measured by the β rays. It will be observed that the time required for the activity in the one case to rise to half its maximum value is equal to the time required in the other to fall to half its maximum value and that this period is equal to 22 days.

118. **Thorium and Th. X.**—Make a dilute solution of thorium nitrate in water. Then add sufficient ammonia to precipitate the thorium as thorium hydroxide. Separate the precipitate and carefully dry it. Also evaporate the filtrate to dryness and remove the ammonium salts from the residue by ignition. The remainder will consist of a very active substance many times more active weight for weight than the thorium salt which was first dissolved. This active constituent has been named thorium X, or Th. X, from analogy with uranium X. Test in the usual way, as soon after preparation as possible, the activity of the precipitated thorium hydroxide and also of the Th. X, and repeat the tests at intervals of about three

times a day for a period of about twelve or fourteen days. Observe that the precipitated thorium has lost a large proportion of its original activity which it had before solution, although it has not lost all its activity. On being tested at intervals, this activity at first decreases for a short time and then begins to rise again and continues to rise until it reaches a maximum, when it remains constant. Test also simultaneously the activity of the thorium X at intervals and observe that at first it increases for a short time and then begins to decrease and continues to decrease until it finally disappears. Plot a curve in each case, showing the relation between activity and time after chemical separation. With the exception of the initial irregularity, which will be accounted for in a later chapter, the curves obtained should be very similar to those obtained in the case of uranium and Ur. X. Note also that the thorium recovers its activity at practically the same rate as the activity of the Th. X decays. The time required for the activity of the thorium to reach half its maximum will be seen to be only about four days, while the same time is required for the activity of the Th. X to decay to half its maximum value.

119. Actinium and Act. X.—If a solution of an actinium salt be made and treated with ammonia in just the same manner as the thorium, a very active constituent will be obtained showing properties very similar to those of Th. X. This substance has been named actinium X, or Act. X, from analogy. If a quantity of the so-called emanium, which is the same as actinium, is available, make a solution of it and treat it in the same way as the thorium was treated. Test the activity of the precipitate and the evaporated residue or Act. X at intervals of once or twice a day for a period of forty or fifty days and observe the recovery of activity of the precipitate and the decay of the activity of the Act. X and plot curves for them as before. Curves of a shape almost exactly similar to those obtained for thorium should result from the tests. The time required for the actinium to regain half its maximum activity and also for the activity of Act. X to decay to half of its maximum value will be found to be about ten days.

120. Theory of Successive Changes.—These results indicate that some process must be continually going on in these substances unaided by any outside agencies. Since the Ur. X, for instance, which gives out β rays can be separated from the normal uranium, leaving it devoid of β rays, therefore the β rays must arise from the Ur. X, and since the uranium regains the β ray activity after being deprived of Ur. X, more Ur. X must be formed in the uranium compound to give rise to the β rays. This can easily be shown to be true, for after the uranium residue has recovered its activity Ur. X can be separated a second time from the compound and the action will be repeated. This separation may be repeated as often as desired after recovery, showing a continuous production. In addition the activity of the Ur. X is not permanent, but gradually dies away. Also we know that the β ray activity of normal uranium, which contains Ur. X from which the β rays arise, does not change, consequently there must be a state of equilibrium in normal uranium in which fresh Ur. X is being formed at the same rate as it dies away in order that the total resultant activity may remain constant. This is borne out by the fact that when the Ur. X is isolated from the normal compound the rate of decay of the separated Ur. X is equal to the rate of recovery of the uranium from which it was separated. In order to maintain this equilibrium state these processes must therefore be going on continuously at a constant rate, and since outside agencies do not affect these processes the cause of the action must arise within the substances themselves.

If the decay curve for Ur. X be studied it will be observed from the form of the curve that the activity decays according to an exponential law. If I_0 represent the initial activity immediately after separation and I_t the activity after a time t, then it will be found that $I_t = I_0 \epsilon^{-\lambda t}$, where ϵ is the natural base of logarithms and λ a constant quantity. Similarly the curve representing the recovery of activity by the uranium from which the Ur. X has been separated can be represented by the equation $I_t = I_0(1 - \epsilon^{-\lambda t})$, where I_0 represents the activity when the maximum is reached and I_t is the activity

recovered at any time t and λ the same constant. The total activity then at any time is a constant.

The results of a large variety of experiments have shown that, as far as tests have been made, neither the rate of decay of the separated product nor the rate of recovery of activity of the substance from which it was separated is affected by the existing physical or chemical conditions such as temperature, etc. After chemical separation has taken place the recovery of activity in one case or the decay of activity in the other proceeds quite independently of any physical or chemical influences to which the substances may be subjected. This indicates that the process arises from some cause within the radio-active substance itself.

Similar processes must of course be going on in the thorium and actinium compounds. As will be seen later conditions of a similar character but differing in some particular exist in the radium compounds.

In the succeeding chapter it will be seen that thorium X, for instance, is not lost when its activity completely decays, but it disappears as thorium X, and in so doing changes into another product or substance which in its turn gives out radio-active radiations. These facts along with a great deal of additional evidence, some of which will be considered later, led to the theory of successive changes in radio-active substances which was formulated by Rutherford and Soddy to explain these curious phenomena. According to this theory the different radio-active substances are gradually undergoing a process of transformation by which they are gradually changing in regular succession from one product to another without the help of any outside agency. The actual amount of material transformed in each instance is extremely small, but the electrical manifestations are so pronounced that they may be detected in very minute quantities. Most of these products give out radiations. In some cases only α rays are emitted and in others only β and γ rays, while in others all three types are produced. The rates at which these changes take place vary very greatly for the different products, some changes requiring

only a few seconds to complete while others extend over a period of several hundred years. The time taken by any one of these changes to be *half* completed is designated the *period* of that transformation or change. The reason for calling half the time of a complete transformation the period instead of the whole time is that it is usually much more convenient to determine experimentally when the change is half completed than when it is fully completed, for during the latter part of the transformation the rate is usually much slower than in the earlier stages, as will be observed from the curves already studied. As this rate of change in the later stages is often so slow it is sometimes difficult to determine the exact time when it is just completed, but this difficulty is not so likely to occur in determining when the transformation is half completed. This theory is called the theory of successive changes, and the different products into which each one is gradually transformed are called transformation products.

CHAPTER XIII.

EMANATIONS.

121. Discovery of Thorium Emanation.—The early experimenters on the radiations emitted by thorium compounds observed a marked difference between thorium and uranium, namely, that while the radiations from uranium were very constant those produced from thorium compounds were very irregular, and anything like constant results could not be obtained from them. This want of constancy was finally traced to the presence of air currents. If the thorium compound was placed in a closed vessel free from air currents the ionization, although for a few minutes at first was somewhat irregular, soon became steady and would remain so, but if a current of air were passed through the vessel the ionization would be greatly reduced. If the ionization were tested in an open vessel where it was subject to air currents the ionization would be quite unsteady. This irregularity was very thoroughly investigated by Rutherford and he found that it was due to the continuous emission of some sort of radio-active particles from the thorium compounds. To these particles the name emanation was given. This emanation is not like the radiations which we have already considered, but it acts in all respects like an ordinary gas, which itself emits rays of the same type as we have been studying. It does not itself consist of ions nor charged particles of any sort, but has the power of producing ions in the gas with which it is mixed by means of the rays which it emits.

122. Some Properties of Thorium Emanation.—Some of the fundamental properties of the emanation may be investigated by means of the apparatus shown in Fig. 64. C is a glass or metal tube about 8 or 10 cm. long and 3 or 4 cm. in diameter. Close the ends with rubber stoppers through which pass smaller glass or metal tubes as shown. In the lower part of C place

a shallow trough containing a quantity of thorium oxide. FH is a testing vessel consisting of a brass cylinder about 30 cm. long and 6 cm. in diameter. K is a central insulated electrode consisting of a brass rod 20 cm. long and connected to an electrometer. Insulate the cylinder FH and connect it to a battery in the usual manner. Connect the cylinders FH and C
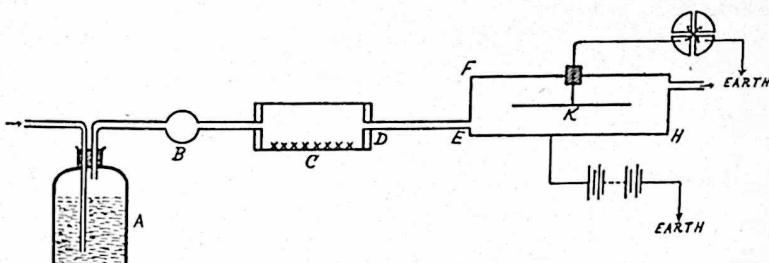
FIG. 64.

by a glass or metal tube a few centimeters long between the points D and E. Pass a slow current of air from a gasometer through a wash bottle A containing sulphuric acid to dry it, and a tightly packed plug of cotton wool in a glass bulb B to remove dust and spray, and thence through the rest of the system.

As soon as the current of air is started test the ionization current in the vessel FH. In all these measurements on the ionization effects of the emanations use the steady deflection method of electrometer measurement described in § 89. If the current of air is maintained steady the ionization in FH will be found to increase during the first few minutes but will soon reach a steady value and remain constant as long as the air current is maintained. Replace the tube between D and E by another one containing a quantity of glass wool and repeat the experiment. Note that the ionization in FH is practically the same as before. Again replace the tube containing the glass wool by a wash bottle containing water, so that the current of air and emanation will have to bubble through the water on the way from C to FH, and again test the ionization in FH. Practically the same value for the ionization should be found as before.

Once more replace the wash bottle between D and E by an insulated metal tube 20 or 25 cm. long and 2 cm. in diameter, containing an insulated electrode along the axis of the tube similar to the one described in § 48. Establish a strong electric field betwen this electrode and the tube and again repeat the ionization tests in FH. Note that the ionization current in FH remains practically the same as before.

These experiments clearly show that the gas in the tube C which is carried into FH possesses some property in addition to being simply ionized, for if we compare these experiments and their results with similar ones performed with uranium (§ 85) and with Röntgen rays (§§ 47, 48) a very essential difference is presented. In the case of the gas being merely ionized by Röntgen rays or rays from uranium the ions were all removed by passing through wool or water or an electric field and no ionization appeared in the testing vessel beyond, but in the present instance the introduction of the glass wool or water or strong electric field produced practically no effect. It cannot therefore be merely ions which are conveyed along with the air, for they would be removed by these agents, but it must be something which is capable of producing ions after it reaches the vessel FH. The emanation mixed with the air behaves just like an ordinary gas in passing through glass wool or a liquid and it is not charged as ions are, for it is unaffected on passing through an electric field. Many other experiments confirm this gaseous nature of the emanation.

123. Diffusion of Thorium Emanation through Solids.—In a lead plate about 6 mm. thick cut a shallow depression 2 or 3 mm. deep and 6 cm. square. Fill this with thorium oxide and cover it with two or three thicknesses of ordinary foolscap paper and carefully wax down the edges to prevent any escape around the edges. Place this in a closed testing vessel of the form shown in Fig. 50, which should be perfectly free from any air currents. Allow it to remain for ten minutes or so and then test the ionization current between the plates. The strong ionization produced cannot be due to the ordinary α rays of the thorium, for they will be practically all cut off by

the paper and the ionization will be found too strong to be accounted for by the β or γ rays. The emanation must therefore diffuse through the paper and ionize the gas above it.

Repeat this test, using, instead of paper, a sheet of aluminium foil about .002 cm. thick. Quite a large quantity of emanation will be found to penetrate even this thickness, which would be sufficient to cut off practically all the α rays from thorium. Other substances in very thin sheets such as cardboard, mica, etc., might also be tried. The emanation will be found capable of diffusing through a number of different substances just as an ordinary gas would do.

124. Nature of Radiations Emitted by Thorium Emanation.—Since the emanation is distributed throughout the gas surrounding the thorium the radiations emitted by the emanation arise from all points throughout the volume of the gas. In order to examine the nature of these radiations experimentally special methods must be used in order to confine the emanation within a definite space and to ionize a definite volume of air free from the emanation. This may be done by the following method due to Rutherford.

AB is a lead box (Fig. 65) about 15 cm. square and 1 cm. deep. In the top of the box cut a hole about 7 cm. square
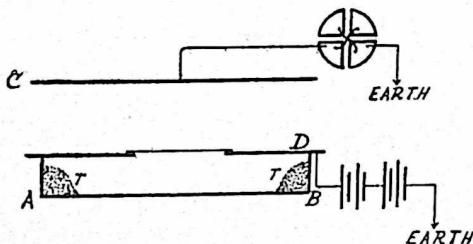
FIG. 65.

and cover it with very thin mica not more than about .0015 cm. thick and carefully wax down the edges. Before closing the box wrap a quantity of thorium oxide in paper and place it in the box in the position marked T remote from the mica window, so that it may be shielded by the lead and so that

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the direct radiations from it may not fall upon the mica. The remaining space in the lead box will soon become filled with emanation after diffusing through the paper. The radiation emitted by the emanation will then penetrate the mica and ionize the air between the cover D of the box and the plate C. The ionization produced between the plates by these rays may then be examined in the usual manner.

Measure the ionization between the plates; then cover the mica with a sheet of the very thin aluminium foil used in the absorption experiments (§ 90) and measure the ionization again. Repeat this, adding a sheet at a time until the radiation is practically all absorbed. It will be found that it requires a thickness of only about .0015 cm. of aluminium to completely absorb all the rays which must therefore be of the α ray type. Since this thickness of aluminium absorbs all the rays given off by the emanation there can be no β or γ rays, for they would penetrate a much greater thickness even after passing through the mica window.

These tests should be made as soon as possible after the introduction of the thorium compound into the lead box, for if it be allowed to stand a few hours the excited activity, which will. be described in the next chapter, will begin to make its appearance.

125. Decay of Thorium Emanation.—The activity of any given quantity of the emanation is not permanent, but rapidly decays with the time if the supply of emanation is not continuously renewed. This may be shown experimentally by means of the apparatus indicated in Fig. 64. Wrap a quantity of thorium oxide in a piece of ordinary foolscap paper which will absorb most of the ordinary radiation from the oxide but will allow the emanation to pass through. Pass a slow current of air, freed from dust and moisture, through the system for about ten minutes until the saturation ionization current in the vessel FH reaches a steady value. Measure this current by the steady deflection method. Then stop the air current and measure the saturation current at intervals of about twenty or twenty-five seconds for a period of about ten minutes. Ob-

serve that this current gradually decreases with increase of time until it finally reaches a zero value. Plot a curve with current values for ordinates and time for abscissæ, taking the maximum value of the ionization current as unity. The curve will be seen to be of the same general form as the decay curve for Ur. X or Th. X, with the exception of the slight initial irregularity in the Th. X curve. The activity of the emanation therefore decays according to an exponential law. This law may be represented as in previous cases by the equation $I_t = I_0 \epsilon^{-\lambda t}$, where I_0 represents the maximum activity, while I_t represents the activity after a time t and λ is a constant. If the measurements are carefully made the period of decay, that is the time taken for the activity to fall to half its maximum value, should be fifty-four seconds.

As has been previously noted, the particles of emanation are not charged, and therefore this decay cannot be due to any removal of the particles of emanation by the electric field. This may be tested by applying different electric fields and the rate of decay will be found to be unaffected. Nor can it be a case of recombination of any sort, since the particles are uncharged, and also the rate of decay is entirely different from the rate of recombination of ions. The loss of activity must be due to a gradual change or transformation of the emanation into some other substance according to the theory of successive changes.

126. Increase of Current with Time.—Place a quantity of thorium oxide covered with a sheet of paper in a closed testing vessel of the form shown in Fig. 50. As soon as possible after the introduction of the oxide, measure, by the steady deflection method, the saturation current and repeat the measurement at intervals of twenty or twenty-five seconds for a period of ten or fifteen minutes. The current will be found to increase with time until it reaches a constant maximum. Plot the usual current-time curve and it will be found to be complementary to the decay curve just studied in the last paragraph, showing that the activity gradually rises to a steady maximum and the rate of increase is the same as the rate of decay of the emanation.

This curve follows an exponential law similar to the recovery curves for uranium and thorium and, using the usual notation, may be expressed by the equation $I_t = I_0(1 - \epsilon^{-\lambda t})$. This curve and the decay curve for the emanation bear the same relation to each other that the recovery curve of thorium bears to the decay curve of thorium X.

What is the significance of this rise of activity? The thorium is continually emitting emanation, and when the thorium is introduced into the testing vessel the amount of emanation gradually increases, as it is not allowed to escape from the vessel. If the emanation did not decay it would continue to increase indefinitely, but since it decays with time the increase continues until the amount produced per second is equal to the amount which disappears per second, and therefore the activity gradually rises until an equilibrium state is reached and the activity then remains constant as long as a constant supply of emanation is available. The period of rise of the activity, that is the time required to rise to half its maximum value, is equal to the period of decay, namely, fifty-four seconds.

127. Radium Emanation.—Not long after the discovery of thorium emanation it was shown that radium compounds also give rise to an emanation possessing properties very similar to the thorium emanation. One respect in which these two emanations differ markedly from each other is in the rate of decay. The emanation from radium takes a much longer time to decay than that from thorium. Somewhat special methods must be used in testing this decay of radium emanation, owing to the formation of what is known as excited activity, which will be discussed in the following chapter. If a quantity of emanation were introduced into a testing vessel and allowed to remain and the activity measured by the method used in the case of thorium this excited activity which gives out radiations would be formed so quickly that the result would be complicated. The effect due to this excited activity may be eliminated by the following method.

Radium chloride dissolved in water gives off much larger

quantities of emanation than in the solid state. Slowly bubble air through such a solution and collect the air mixed with emanation in a gas holder over mercury. As soon as the gas holder is filled draw off a measured amount of this air mixed with emanation in a gas pipette and introduce this measured quantity into a testing vessel of a form similar to the one shown in Fig. 64, which must be air-tight. Measure immediately the ionization current and then blow the air and emanation out of the vessel so that it may not remain in the vessel any length of time. At intervals of twelve or fifteen hours for a period of about twenty-five or thirty days repeat this operation, drawing off the same measured amount of air and emanation, introducing it into the testing vessel and measuring the current. Plot the usual current-time curve and note its similarity to the corresponding curve for thorium emanation. In this instance, however, the period of decay is very much longer, being 3.75 days instead of fifty-four seconds. This difference in period very clearly differentiates these two emanations. The activity of the radium emanation is due to the emission of α rays just as in the case of thorium emanation.

128. **Rise of Activity of Radium.**—Dissolve a small quantity of radium chloride in water and bubble a current of air through the solution for a few hours, so as to remove the emanation from it. Then evaporate the solution to dryness and test the activity of the residue. Test this activity at intervals of twelve or fifteen hours and observe the gradual increase with time. Continue these tests over a period of about twenty or twenty-five days and plot the usual current-time curve. This curve should be found to be complementary to the decay curve, as in the case of thorium and the rate of recovery of activity equal to the rate of decay of the emanation. This, of course, is due to the gradual production of emanation, which accumulates until an equilibrium state is reached, when the rate of production is equal to the rate of decay.

129. **Actinium Emanation.**—Actinium compounds also give rise to an emanation possessing properties similar to the other emanations. The most distinguishing characteristic of it is its

period of decay, which is extremely short and consequently somewhat difficult to measure. It decays to half value in the short period of 3.7 seconds. Like the other emanations, its activity is due to the emission of α rays.

130. Effect of Conditions on Emanating Power.—The different compounds of thorium vary greatly in the amount of emanation given off under ordinary conditions. Although the percentage of thorium present in a given weight of the compound may not be very different in the various compounds, yet the amount of emanation given off by equal weights of the different compounds varies enormously. For instance, thorium nitrate in the solid form emits only about $\frac{1}{600}$ as much emanation as the same weight of thorium hydroxide. Even different preparations of the same compound vary somewhat among themselves. The oxide of thorium is one of the most powerfully emanating compounds of thorium. The different compounds of radium also show differences in emanating power.

The amount of emanation given off is, however, independent of the nature of the gas surrounding the emanating body. If the ionization current due to the rays from the emanation be measured in different gases it will of course vary with the nature of the gas, but this is due to the different amount of ionization produced in different gases by the same rays, and not to any difference in the amount of emanation present.

The rate of emission of emanation is also independent of the pressure of the gas. Wrap a quantity of thorium oxide in paper to absorb the α rays given out by the thorium itself and place it in an air-tight vessel of the form represented in Fig. 50. Measure the saturation current at different pressures and it will be found to vary directly as the pressure. But the ionization produced by any radio-active source is proportional to the pressure and therefore the source in this instance, which is the emanation, must be independent of the pressure of the gas.

The emanating power of a compound of thorium or radium depends upon the state of moisture of the gas surrounding the

compound. The emanating power is greater in a moist gas than in a dry one. The introduction of moisture into the surrounding gas will increase by several times the amount of emanation given off.

If the emanating compound be placed in solution the emanating power is enormously increased. In some cases it will be increased several hundred times by simply dissolving the radium or thorium compound in water. Experiments show that this is really not due to a difference in the rate of production in the solid form and in the dissolved state, but that in the solid form the emanation when produced is occluded in the solid and not allowed to escape so rapidly, while in the solution it escapes much more easily. Therefore, to obtain large quantities of emanation it is always advantageous to place the emanating compound in solution.

Temperature is a very important factor in connection with the emanating power of different compounds. If ordinary thoria, for instance, be placed in a platinum tube and gradually heated up to a dull red heat the rate of emission of emanation will gradually increase to several times its original value and will continue to escape at that rate if the temperature is maintained constant. When the temperature is lowered again the rate of emission of emanation will return to its original value. Also if the temperature is reduced to the neighborhood of — 80° C. the emanating power is reduced to only a small fraction of its value at ordinary temperatures, but is restored again when the temperature returns to its ordinary value.

If the thoria, for instance, in the platinum tube be heated to a white heat, a remarkable change takes place. At this high temperature the emanating power is greatly decreased and on cooling the thoria does not regain its emanating power, but it is permanently reduced to only a small fraction of its original value. This de-emanating, as it is called, of the compound is permanent, but its original power of emitting emanation may be restored by dissolving the compound and then separating it from the solution. Radium compounds may also be de-emanated and afterwards restored by a similar process.

131. Condensation of the Emanations.—These emanations act in all respects like gases. One of the most conclusive proofs of their gaseous nature lies in the fact that they may be condensed by very low temperatures. Rutherford and Soddy were the first to show this experimentally and used the following method: The radium emanation is stored in a reservoir R (Fig. 66) and may be forced out of the reservoir by raising
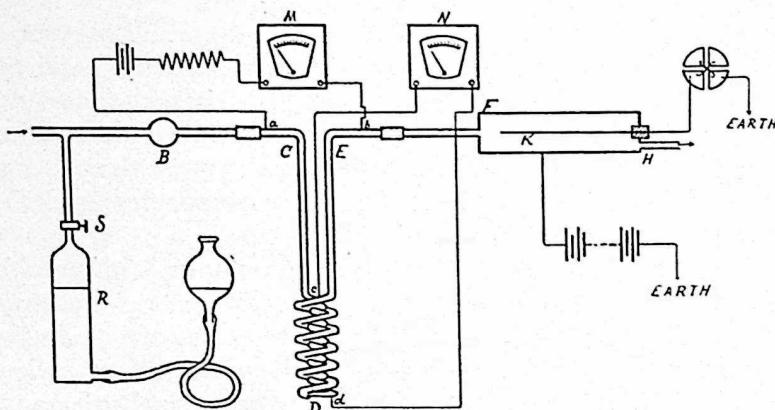
FIG. 66.

the level of the liquid. This is connected through the stopcock S to the horizontal tube above through which a steady stream of gas may be sent from a gasometer and on its way passes through a bulb B containing drying material. CDE is a spiral made from a copper tube of a total length of 310 cm. and internal diameter of 2 mm. FH is a cylindrical testing vessel of the usual form containing an insulated electrode K, so that by connecting this electrode to the electrometer and the cylinder to a battery any ionization current produced in the cylinder may be measured. If the stopcock S be opened and the liquid in R be raised while a slow stream of gas is passed along the horizontal tube the emanation will be carried through the spiral D and into FH, where an ionization current will be produced. If the copper spiral D be immersed in liquid air the emanation will not reach the ves-

sel *FH,* as will be indicated by the fact that, although the current of gas is still flowing, the ionization current in *FH* ceases. If while the spiral *D* is immersed in the liquid air the stopcock *S* be closed so as to shut off the supply of emanation and then the spiral be removed from the liquid air while the stream of air through the system is still flowing, there will be, shortly after removal, a sudden movement of the electrometer needle indicating a sudden production of ions in *FH*. These experiments show that when the spiral tube is immersed in the liquid air the emanation which previously passed through along with the air is condensed and remains in the spiral, but when removed from the liquid air and its temperature allowed to rise the emanation volatilizes and is then carried over into *FH* and manifests itself as usual by producing ions.

The temperature at which the emanation volatilizes was determined in the following manner: A current of about 0.9 ampere from a storage battery was sent through the spiral by leads soldered to the points *a* and *b* and this current was measured by a Weston ammeter *M*. Two potential leads were soldered to the points *c* and *d* and the potential read by a millivoltmeter *N*. Any change of resistance in the spiral due to change of temperature could be determined from the current and drop of potential. The copper spiral was thus used as a resistance thermometer, and was carefully calibrated by measuring its resistance at the known temperatures of the boiling and freezing points of liquid ethylene and the boiling point of liquid air. After calibrating the spiral a quantity of emanation was condensed in it by immersing it first in a liquid ethylene bath and then still further cooling this bath by liquid air. The temperature was then allowed to rise slowly, and when the emanation made its appearance in the testing vessel *FH* the temperature of the spiral was determined. It was found that the radium emanation volatilized at — 150° C.

Thorium emanation, on account of its very rapid rate of decay, presents considerable difficulty in the determination of the temperature at which it condenses or volatilizes. In the time required to make observations a very large proportion of its activity will have decayed and consequently it is extremely

difficult to make definite measurements. By using special ·
methods however Rutherford and Soddy found that the thorium
emanation began to condense at — 120° C., but that some of
it might escape condensation even as low as — 150° C.

132. Decay of Emanation at Low Temperatures.—The rate
of decay of the activity of these emanations at the temperature
of liquid air, that is, while they are condensed, has also been
determined, and it is found that the rate of decay is unaltered
at this very low temperature, and even the fact of the ema-
nations being condensed does not affect the rate of decay. The
activity of the emanation in the condensed form decays at just
the same rate as in the gaseous form.

This may be easily tested in the case of radium emanation.
Pass a known quantity of emanation through the system (Fig.
66) into the testing vessel at ordinary temperatures and meas-
ure its activity. Then condense an equal quantity in the spiral
and leave it in the condensed state for a known interval and
then after allowing it to volatilize pass it into the testing vessel
and measure its activity. Repeat this at increasing intervals
and determine the regular decay curve. For this purpose the
emanation should be derived from a constant source, that is,
from a vessel containing a solution of a radium compound
which is continually giving off fresh emanation, for if the
emanation be stored in a separate vessel its activity will of
course decay and the source of activity will not be constant.
Similar results may be obtained with thorium emanation, but
the experiments have to be made very rapidly and by special
methods as the rate of decay is so extremely rapid.

133. Phosphorescent Action of the Emanations.—The ema-
nations show marked phosphorescent phenomena similar to the
phosphorescent action of other radio-active bodies. This may
be shown by placing a small quantity of moist radium bromide
on a zinc sulphide screen. The luminosity will spread over the
surface of the screen as the emanation diffuses around and
the luminosity can-be made to move about by gently blowing on
the screen. If the moist radium compound be placed in a glass
tube and a stream of air passed through the tube a zinc sul-
phide screen placed at the mouth of the tube will be brightly

illuminated by the emanation. A variety of materials show this phosphorescent action when the emanation comes in contact with them.

This action is also quite marked at even the low temperature of liquid air, which may be demonstrated in a very interesting manner. Place a quantity of willemite crystals in a glass U tube of about 8 mm. diameter. Connect this to a reservoir containing a supply of radium emanation. Immerse the U tube in liquid air and pass a quantity of emanation through the tube. The emanation by being condensed will be left behind in the tube. If the tube be removed from the liquid air it will be found that the crystals nearest the end where the emanation entered the tube show luminosity while those at the other end do not. If the ends of the tube be closed and the temperature allowed to rise this luminosity will gradually diffuse throughout all the contained crystals. This indicates that the emanation by being condensed near the beginning of the crystals does not reach those farther along the tube, and produces luminosity at this point even at this low temperature, but when the temperature rises the emanation volatilizes and is able to diffuse throughout the tube and produces phosphorescence in the remaining crystals. The movement of the emanation through the tube can thus be followed by the eye.

After the volatilization takes place and the tube is filled with the emanation it may be partially concentrated at any point by applying to the outside of the U tube a piece of cotton wool saturated with liquid air. The tube is thus cooled locally by the liquid air and the emanation condenses and is concentrated at that point.

134. Source of the Emanations.—In a thorium compound in equilibrium both thorium and Th. X are present. Which of these is the direct source which gives rise to the emanation? If the thorium X be separated in the usual way from the thorium compound the thorium residue even in solution will at first emit no emanation, but the solution containing the Th. X will possess unusual emanating power. Not only so, but the thorium residue will gradually regain its emanating power, while the Th. X gradually loses its

power of emitting emanation. The rate at which the thorium regains its emanating power is the same as the rate of decay of the emanating power of the Th. X. In addition, these rates of recovery and decay of emanating power are exactly the same as the rates of recovery and decay of the radio-activity of thorium and Th. X respectively. These results show then that, since no emanation is produced just after the Th. X is removed and the Th. X itself possesses strong emanating power, and besides, since the rise of activity of thorium residue is due to the production of Th. X and also the thorium regains emanating power at the same rate that its activity is regained, that is at the same rate that Th. X is produced, the emanation must arise directly from the Th. X and not from the thorium itself. Since the activity of the Th. X and its emanating power decay at the same rate the activity of Th. X is therefore proportional to its emanating power. According to the theory of successive changes then the production of emanation must be a result of the decay of Th. X, that is, the Th. X must be gradually changing spontaneously into the emanation. Th. X and the emanation have distinct chemical and physical properties and have quite distinct rates of decay, one being 3.7 days and the other 54 seconds. They are therefore entirely distinct substances.

Similar remarks apply to Act. X and actinium emanation. The latter arises directly from the Act. X.

There is a difference in the case of radium emanation, for no substance has as yet been discovered in connection with radium corresponding to Th. X or Act. X. As far as is known there is no such product as radium X. Radium emanation, unlike the other two, arises directly from the radium itself without any other product intervening. According to the same theory the radium is continuously changing into emanation, but as will be seen later the rate of change is extremely slow.

Since these emanations are decaying at a more or less rapid rate they must, on following out this theory of successive changes, be going through a similar process of transformation into some other product. This will be seen in the following chapter to be the case.

CHAPTER XIV.

EXCITED ACTIVITY.

135. Active Deposit.—If a solid body be exposed in a closed vessel to the emanation from thorium, radium or actinium its surface becomes coated with an extremely thin, solid deposit of material which is intensely radio-active. This *active deposit,* as it is called, is a very extraordinary substance and possesses remarkable properties, the study of which has thrown an immense amount of light on the processes going on in radio-active bodies.

In an air-tight vessel, Fig. 67, about 25 cm. square place a heavy lead block *C* about 8 cm. square and 12 cm. high. In the top of this cut a recess into which a small beaker *D* may fit. In this beaker put a solution of either a thorium or radium compound. At different positions, such as *E, F* and *H,* place plates of metal about 3 or 4 cm. square and close the vessel and leave them for six or eight hours. At the end of this time

Fig. 67.

remove each of the plates separately and placing them in a testing vessel of the form in Fig. 50, test them for radio-activity. Observe that they are not only radio-active, but that the plates from the different positions in the vessel possess practically the same amount of radio-activity when tested immediately after removal from the vessel *AB.* These plates have thus acquired radio-active properties while in the vessel. This acquired property cannot be a result of the direct radiations given off by the radio-active body in *D,* for the plate *H,* which was entirely shielded from these rays by the lead block, is just as active as *E,* which was in the direct line
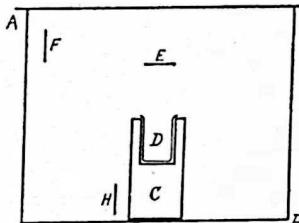
of the rays. It must be due to something which is distributed equally throughout the vessel and the only radio-active material which is thus equally distributed is the emanation.

Make a similar test for plates made of other materials, both conductors and non-conductors. The amount of activity acquired in the same time should be practically equal in all cases. This acquired radio-activity therefore does not depend upon the material on which it is deposited.

136. Concentration on Negative Electrode.—In an air-tight metal vessel *AB*, Fig. 68, place a quantity of powdered thorium oxide or a solution of radium bromide contained in a glass crystallizing dish. The top of the vessel should consist of a plate which is removable. In the top of this plate insert a short metal tube *ab* about 2 cm. in diameter. Make an ebonite stopper to fit this tube and pass a stout wire *D* through
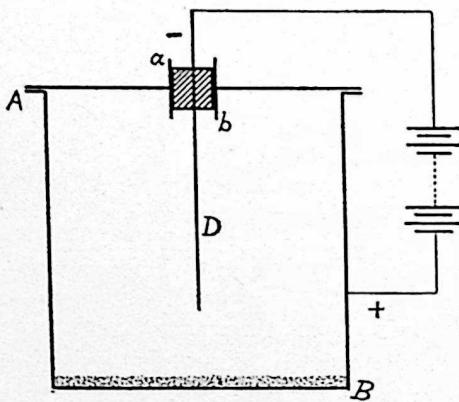
FIG. 68.

this ebonite stopper. Place the wire in position and close the joints in the cover with wax and connect the wire to the negative pole of a battery of two or three hundred volts while the vessel *AB* is connected to the positive pole of the battery. Allow the system to remain thus for several hours. Then remove the ebonite stopper and wire (closing the tube with another stopper to prevent the escape of emanation) and test

the activity of the wire in the testing vessel (Fig. 50) and note that it is intensely radio-active. Repeat the experiment for the same length of time, but in this case connect the wire to the positive pole and the vessel to the negative pole of the battery. On testing the wire after the same time of exposure it should be practically free from any activity if it has been exposed to thorium emanation, but will possess a very little if radium emanation were used. Repeat the experiment again without connecting either wire or vessel to the battery. On testing the wire under these conditions it should possess some radio-activity, but not nearly so much as when the wire was charged negatively. This active deposit from whatever source it is derived may be concentrated on a negatively charged electrode but not on a positively charged one, except to a very slight extent in the case of radium. By this method of concentration a thin wire may be made several thousand times more active per unit area of surface than the active compound from which it is derived.

This radio-activity which is thus produced in a non-active body by exposure to an active substance is usually called *excited radio-activity*. It will be shown later that this activity arises from a material deposit called the *active deposit*.

137. Source of Excited Activity.—It has been noted incidentally in § 135 that the emanation is the most probable source from which the excited activity can arise. This conclusion is confirmed by a further study of the conditions governing its production.

In the bottom of the apparatus, Fig. 68, place the thorium compound or the radium solution in a shallow vessel which may easily be covered over. Cover this vessel with several sheets of paper which will cut off the α rays, but will allow the emanation to diffuse through. Connect the central wire to the negative pole as before and after a sufficient time test for the concentrated activity on the wire. It will be observed that the cutting off of the α rays produces no diminution in the amount of active deposit on the wire. The active deposit can not arise then from the α radiation emitted by the thorium or

radium. Now cover the vessel with a sheet of mica and care-fully wax it down to make it gas-tight, so that no emanation at all may escape, and repeat the previous test. Observe that this time no excited activity is obtained on the wire. This indicates that the emanation is essential to the production of the active deposit. This conclusion is further supported by the fact that uranium and polonium, which do not emit any emanation, do not produce any active deposit while radium, thorium and actinium, all of which give out emanations, pro-duce excited activity in bodies exposed to their emanations. In addition to these facts the amount of excited activity pro-duced is always proportional to the amount of emanation present. This fact may be very easily shown in the case of radium emanation, since it has a long period of decay. Store a quantity of radium emanation mixed with air in a reservoir and at intervals of six or eight hours introduce a measured quantity of emanation into the vessel of Fig. 68, and concen-trate the active deposit on the central wire. At each suc-cessive interval the amount of excited activity produced on the wire will be found to be less than the amount deposited during the preceding interval. The rate at which the emanation decays with the time has already been measured, and if the amount of active deposit be measured by the current which it produces, at each succeeding interval it will be found to be proportional to the amount of emanation present at the corre-sponding time. If the different emanating bodies be examined it will be found that the amount of excited activity which they are capable of producing is always proportional to their ema-nating power.

This accumulation of facts shows conclusively that the active deposit must arise from the emanation in each case. In the light of the theory of successive changes, as will be shown later, the emanation in decaying is really changing into the active deposit which forms a further link in the chain of suc-cessive transformations.

138. **Decay and Rise of Excited Activity from Thorium.**— Expose a negatively charged wire in the vessel of Fig. 68 con-

taining thorium oxide for a period of twelve or fourteen hours. Then remove it and place it in the testing vessel of Fig. 50 and test its activity at intervals of about four hours at the beginning and later at somewhat longer periods. Plot a time-activity curve. The activity will be found to decay as the time advances and the form of the decay curve will show that the decline in activity takes place according to an exponential law of an exactly similar nature to that representing the law of decay in the other radio-active products already studied. The time required for the excited activity to fall to half value will be observed to be eleven hours.

Expose a fresh negatively charged wire to the thorium emanation for an interval of only one hour, and, removing it, test its activity as quickly as possible. Replace it as soon as possible in the emanation again and leave it for another hour, and remove and test again as quickly as possible. Repeat this at intervals of two or three hours for a period of about twenty or thirty hours, and after that at longer intervals for about three days. Plot a time-activity curve and observe that the activity gradually increases with the time of exposure to the emanation until it reaches a steady maximum. Note also that, except for a little irregularity at the beginning, this curve is complementary to the decay curve obtained above. These two curves bear to each other a relation exactly similar to that which the decay and recovery curves for Ur. X, Th. X or the emanations, bear to each other. It takes time for the active deposit to be produced from the emanation and the amount of the deposit, as measured by the excited activity, increases until the equilibrium state is reached, when the rate of production is equal to the rate of decay.

In all the measurements on the excited activity great care must be taken to ensure that the air in the vessel containing the emanation in which the wire is exposed is free from dust, as dust particles cause the active deposit and its activity to act in a very capricious manner.

If instead of exposing the charged wire to the emanation for a period of several hours the interval of exposure be

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reduced to only a few minutes a different phenomenon presents itself. Expose the negatively charged wire in the emanation vessel for about thirty-five or forty minutes and remove it and test its activity at short intervals of twenty minutes or so, and plot the usual time-activity curve. It will be found that the activity, instead of beginning to decay after removal, at first increases in a marked degree for three or four hours until it reaches a maximum, and after that decays according to the ordinary exponential law, decaying to half its maximum value in the same time as before, namely eleven hours. If the time of exposure be made a little longer this initial rise after removal will not be so marked, and the longer the exposure the less marked will this initial rise in activity be, until for a long exposure, as already seen, the decay begins immediately after removal and no initial rise is observed.

139. Explanation of the Decay Curves of the Active Deposit from Thorium.—The marked difference between the decay curves for a short and a long exposure indicates that the process of transformation, according to the general theory of successive changes, is in this instance somewhat more complicated than in the cases previously studied. Since, in the case of the short-exposure, the activity at first increases, there must be a production of active matter after the removal from the influence of the emanation. It appears as though there is at first a change taking place from either a non-active or very slightly active substance to a more active one to produce the increased activity. These phenomena may be very easily explained on an assumption of the following nature: Suppose that the active deposit is not a simple substance but a complex one consisting of a mixture of at least two substances which have been named by Rutherford thorium A and thorium B, and suppose that thorium A arises directly from the emanation and is first deposited on the wire and then changes into thorium B, and finally thorium B then changes into something else. For a short exposure the deposit will consist almost entirely of thorium A, as very little of it has had time to change into thorium B. If we also suppose that thorium A either gives

out no rays at all or rays which produce a very small amount of ionization compared with those from thorium B, then the activity at first will be very small, due almost entirely to the very small portion of thorium B present. If thorium A changes into thorium B, which in turn decays, then the activity will increase until a maximum is reached, when the change of A into B just balances the decay of B. Then beyond this stage as more atoms of B will change per second than are produced from A the total activity will gradually decrease. In the case of the long exposure this maximum has been reached before removal from the emanation, and consequently no initial rise is observed.

It was thought for some time after discovery that thorium A emitted no rays at all and it was termed a " rayless " product, but it has recently been shown that it emits a slow-moving type of β rays whose ionizing power is very weak. These two substances have been separated by special means and have been shown to be two distinct substances which have distinct periods of change, thorium A being half transformed in eleven hours while thorium B requires only one hour.

Still more recently it has been shown that thorium B is itself not a simple substance, but consists of at least two substances which have been called thorium B and thorium C, the former being the parent of the latter. Some very recent experiments of Hahn indicate that this list may be still further extended to include another product called thorium D. Thorium B emits only α rays, while thorium C emits not only α rays but very probably β and γ rays also.

140. Decay and Rise of the Excited Activity from Radium. —An examination of the active deposit from radium emanation shows an even more complicated state of affairs than exists among the thorium products. The decay curves measured by the different types of rays show distinct differences and even the form of the curves indicate peculiarities not present in the curves for thorium.

The following method of obtaining the active deposit from radium for a series of experiments will be found most con-

venient.   Dissolve a quantity of radium bromide in water in a
bottle of about three times the capacity of the solution.   Fit
the neck of the bottle with an ebonite stopper.
Through a hole in this stopper pass a wire A
of somewhat smaller diameter than the hole as
shown in Fig. 69, and on this wire fit a collar
which will allow the wire to pass through the
stopper to a definite distance above the solution.
When in place the openings in and around the
stopper may be sealed with wax.   Connect this
central wire A to the negative pole of a battery
of two or three hundred volts, while the other
pole of the battery is connected through a large
resistance to earth.   Connect the solution in the
bottle to earth by the wire B which dips into
the solution.   The emanation collects in the
space in the bottle above the solution and the
active deposit collects on the charged wire
suspended above the dissolved radium.
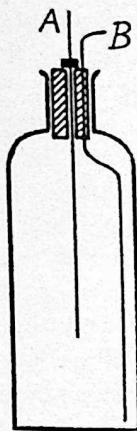
FIG. 69.

Expose this wire for about twenty-four hours to the emana-
tion.   Remove it and make it the central electrode A in a metal
cylinder of about 4 cm. diameter, as shown in Fig. 70.   Make
connections as shown in the diagram.   Around the electrode A
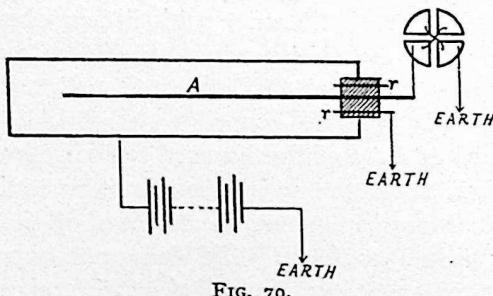
FIG. 70.

and insulated from it and from the cylinder is a metal guard-
ring rr connected to earth to prevent any leakage from the
battery to the wire.   Using the steady deflection method meas-

ure the activity of A at intervals of about two minutes for a period of about one and a half hours and plot the usual decay curve. In the meantime, while these measurements are being made, expose a similar wire for a period of about an hour and then determine its decay curve as soon as the first determination is finished. Make a third exposure of ten minutes and determine the corresponding curve. Plot these curves on the same scale and compare them. The ionization current in these cases is due almost entirely to α rays which might be tested if desired by the usual absorption method. Note the rapid initial drop in the curves and then the slower rate of decay for a time, and then afterwards the rate begins to increase again. Observe that the shorter the exposure the slower is the rate of decay after the initial rapid drop.

Now repeat these experiments for exactly the same times of exposure, but instead of measuring the activity by means of the α rays, using an electrometer, test the activity by means of the β rays emitted by the active deposit. To do this use an electroscope of the type shown in Fig. 14, and cut a hole in the bottom of this electroscope and cover it with a sheet of aluminium foil thick enough to absorb all the α rays, and then place the active wire just underneath the foil which will allow the β and γ rays to pass through and ionize the air inside the electroscope. The β rays will however produce by far the greater part of the ionization. The decay curves measured by the β rays will be found quite different from those measured by the α rays. The β ray activity of the deposit obtained by long exposure will begin to decay at once, but comparatively slowly, while the activity of the deposits by short exposure will at first increase to a maximum and then decrease. The shorter the exposure the greater will be the increase, but after the maximum is reached the rate of decrease will be practically the same for all exposures, even for the deposit by long exposure.

These experiments should be repeated once more, measuring the activity of the deposit by the γ rays alone. To do this set the electroscope on a lead plate about 6 mm. thick, which

will absorb both the α and β rays, and the ionization in the electroscope will be due to the γ rays alone. Obtain curves for exactly the same times of exposure using the γ rays. These curves will be found to be identical with those obtained from the β rays. This shows that whatever the changes taking place the β and γ rays always occur together.

141. Explanation of the Decay Curves of the Active Deposit from Radium.—The peculiar shape of the decay curves as determined by the α rays along with the totally different shape of those determined by the β and γ rays indicate that the active deposit from radium must be very complex. The α ray curves all show a very rapid initial decay for about the first ten minutes, followed by a very much slower rate for about thirty or thirty-five minutes, and this in turn is followed by a somewhat more rapid rate of decay. The β and γ ray curves show, except in the case of long exposure, an initial rise in activity for about fifteen or twenty minutes, followed by a decay. By a process of analysis partly theoretical and partly experimental and of a somewhat lengthy nature, the details of which are however beyond the scope of this course, it has been shown that the active deposit from radium emanation consists in the first instance of three distinct substances which have been named radium A, radium B and radium C. Radium A emits only α rays and in decaying changes into radium B, requiring only three minutes to be half transformed. Radium B emits β and γ rays and has a period of twenty-six minutes, while radium C gives out all three types of radiations and is half transformed in nineteen minutes. The fact that radium A emits no β or γ rays accounts for the initial rise in the β or γ ray curves for short exposure. For a short exposure most of the deposit consists of radium A, and therefore the β or γ ray activity is very small, due only to the small amount of radium B or C present. Radium A changes rapidly into radium B, which in turn changes into radium C, both of which give out β and γ rays, and therefore the β and γ ray activity increases, until finally the rate of decay of radium C is greater than the rate of supply, and therefore there is a total gradual decrease.

In the case of the α ray curves the α radiation from radium A rapidly decays as radium A changes into radium B which gives out no α rays, but it in turn very soon changes into radium C, which again increases the supply of α rays and prevents the decay of the α radiation from being so rapid. But finally all the radium A and B are changed into radium C, · and as it changes the α ray activity again diminishes more rapidly.

142. Active Deposit of Slow Change.—After the greater portion of the excited activity of the deposit from radium has disappeared, which, as we have seen, takes place in a few minutes, there remains a residual activity which decays extremely slowly. This residual activity is only a very small fraction of the original activity of the deposit immediately after removal from the emanation. It varies somewhat with the conditions but is of the order of about 1/300,000 part of the original activity, being under some circumstances much less than this and under others greater.

If a platinum plate be exposed to the radium emanation for a period of about a week and then removed and its activity tested the rapid decay of the activity already studied will be observed. After an interval of two or three days this rapidly decaying activity will have all disappeared, but a small residual will remain. If this residual activity, as measured by the α rays, be measured it will be found to increase very slowly, and continue to increase for several months, but finally, after a long period, will approach a maximum. If, however, the activity be measured by the β rays it reaches a maximum in a much shorter interval of only about a month. These results, along with other determinations extending over lengthy periods, indicate that this residual active matter is a complex substance, consisting of slowly changing products. The results of experiments up to date show that this residual deposit consist of four distinct products, which by analogy have been named radium D, radium E, radium F and radium G.

The periods of transformation for these four products are very slow compared with those for radium A, B and C. Ra-

dium D and radium E do not emit any rays, and are therefore rayless products and are half transformed in forty years and six days respectively. Radium F emits β and γ rays and has a period of four and a half days, while radium G emits only α rays and its period is 140 days. These four products are called collectively the active deposit of slow change, while radium A, B and C form a group called the active deposit of rapid change.

143. Active Deposit from Actinium.—A negatively charged wire exposed to the emanation of actinium receives an active deposit possessing properties very similar to the active deposit from thorium. This active deposit from actinium may be studied experimentally in a manner similar to that described in the case of thorium, and it will be found that it is also complex, consisting of three distinct products which have been called actinium A, actinium B and actinium C. The periods of transformation are all comparatively short, being 36 minutes, 2.15 minutes and 5.1 minutes, respectively. Actinium A emits β rays, actinium B only α rays, while actinium C emits β and γ rays.

144. Some General Properties of the Active Deposits.—If a wire which is to be made radio-active is carefully weighed before and after exposure to the emanation no difference in weight will be detected, no matter how long the exposure may be, or if the active wire be examined under the microscope no trace of foreign matter will be observed. These facts alone might lead to the conclusion that what has been called a deposit is really not of a material nature. Other facts, however, show that it is really a material deposit, but is extremely minute in quantity and it would in all probability escape detection if it were not for its power of emitting radiations. If a wire carrying an active deposit from radium be drawn across a zinc sulphide screen a brightly luminous trace is left behind, which continues for some time, indicating that some of the active matter is rubbed off and left on the phosphorescent screen. The deposit may also be partially rubbed off the wire by rubbing with a cloth, and almost completely removed by rubbing

with sand paper, and after rubbing the deposit will be found on the sand paper.

A large portion of the deposit may also be dissolved off the wire by dipping the wire in hydrochloric or sulphuric acid. If the acid be then evaporated the active deposit is left behind on the vessel and has not been altered in its properties. The active deposit decays at the same rate while in solution in acid as it does in the undissolved state.

If a wire containing the active deposit be heated to a white heat the activity disappears from the wire. The activity is not destroyed, for if the wire be surrounded by a cylinder while being heated the activity will be found on the cylinder after heating. This shows that at this high temperature the active deposit becomes volatile and is transferred from the wire to the cylinder.

145. Some other Transformation Products.—Recent investigations, some of which have extended over a considerable time, have revealed still other intermediate transformation products belonging to these already large families of radioactive substances. An intensely active body which has been called radiothorium has been found in the thorium family. It is intermediate between thorium and thorium X, and is the immediate parent of thorium X. It emits α rays and has a period of transformation of 800 days.

In addition to this there is another body existing between thorium and radiothorium, which was at first thought to be a single substance and was called mesothorium, but quite recently this has been still further analyzed by Hahn and found to be complex, consisting of two substances for which the names mesothorium 1 and mesothorium 2 have been suggested. Mesothorium 1 arises directly from thorium and is a rayless body having a period of 5.5 years and gives rise to mesothorium 2 which emits β and γ rays. Mesothorium 2 is half transformed in about 6.2 hours, and in so doing changes directly into radiothorium.

In the actinium series there exists between actinium and actinium X a substance of similar properties to radiothorium

which from analogy has been called radioactinium. It emits α rays and is the immediate parent of actinium X.

One of the most recent discoveries in this connection is that of a product which finds a place in the series between uranium and uranium X. It has been proposed to call it radio-uranium, and it is considered to be the immediate parent of uranium X. Its properties have not as yet been completely investigated.

From a variety of indirect evidence it has for a long time been thought that there was a close relation between uranium and the radium family. Many attempts have been made to prove this experimentally, but with somewhat indifferent success. Recently however an active body which has been called ionium has been located in uranium minerals and has been pretty well proved to be the connecting link. It is thought that this ionium arises directly from uranium X, and is in turn itself the immediate parent of radium. The uranium and radium families then form one complete series with ionium as the connecting link.

146. Theory of Radio-active Changes.—From a study of the various radio-active substances individually and in their relation to one another we have seen that there are a series of continuous changes from one substance to another taking place which so far have never been observed in any other class of materials. Each of these substances is entirely distinct from the others and has distinct physical and chemical properties. They are not permanent substances however, but gradually decay, and each one has a distinct and definite period of decay which is its most distinguishing property and by which it is differentiated from all the others. These changes from one substance to another take place without the aid of any outside agency and in fact are practically unaffected by any external influence. How do these remarkable changes come about? Rutherford and Soddy were the first to offer a satisfactory theory to explain these phenomena. The disintegration theory or theory of successive changes which they put forth in the year 1902 and which has since been developed is now the generally accepted one.

Radio-active properties have been shown to be properties of the atom and not of the molecule, for the activity of radium, for instance, depends upon the amount of the element present and not upon its chemical combination with other elements. According to the general theory of J. J. Thomson an atom of any substance may be considered a complex structure consisting of positively and negatively charged particles in rapid rotation within its own system and held together by their mutual forces in equilibrium. For such a system to be permanent it must be in stable equilibrium. According to the disintegration theory this complex structure, constituting the atom of radium (which we shall take as the typical example), becomes by some means unstable and one of the positively charged α particles is suddenly expelled with great velocity. This α particle constitutes the radio-active radiation from radium. The structure of the atom which remains is now different and constitutes the atom of a new substance, namely, the emanation. These atoms of the emanation are unstable and gradually change by the expulsion of another α particle from each atom. The remaining atom now in turn constitutes the atom of a new substance, namely, radium A. These atoms in their turn break up as before, changing into radium B and the process is continued throughout the successive changes. The processes are not identical in all instances, for in some cases an α particle alone is expelled but in others negatively charged β particles are expelled accompanied by γ rays, while in other cases the change consists in giving out all three types, α, β and γ rays. The production of one radio-active product from another consists, according to this theory, in the disintegration of the atom by the expulsion of a positively or negatively charged particle or both owing to the system of which the atom is composed becoming for some reason unstable. The radio-active property of the substances is the result of this disintegration by expulsion of charged particles. The radio-activity is an accompaniment of the disintegration of the atoms.

Why do these atoms suddenly become unstable and break up without any apparent cause? Several explanations have

been offered to account for this, but the most probable one seems to be that if this system of charged particles, of which the atom in all probability consists, is in rapid rotation it must be radiating energy, and when sufficient energy has been radiated the mutual forces of the system no longer balance and one or more of the particles escape and cause disintegration.

These atoms of the radio-active substances have an independent existence and distinct physical and chemical properties, but they differ from the atoms of ordinary non-radio-active elements in the fact that they are not permanent. These products are however just as truly elements while they last as are the non-radio-active elements. To distinguish these unstable atoms from the ordinary atoms the term metabolon has been suggested as a convenient name.

We have observed in a few instances that the transformation products do not emit any rays at all, and the change from them into the succeeding substance apparently takes place without the expulsion of any particles. These " rayless " changes may be explained in either of two ways. The new product may be formed simply by the rearrangement of the system of charged particles among themselves within the atom without the expulsion of any of them. The new atom may consist of the same set of particles arranged under a new system. This rearrangement may not take place with sufficient violence to expel any of the members of the system.

Another hypothesis which would explain the rayless change is that it may be caused by the expulsion of one or more charged particles, but with a velocity too slow to ionize the gas. Experiments show that when the velocity of the α particle falls below 10^9 cm. per second it ceases to ionize the gas, and consequently an α particle expelled with a velocity below this minimum would escape detection, since it produces no ions. The so-called rayless change thus might be caused by the expulsion of an α particle with a velocity below the minimum necessary to produce ions. This hypothesis receives some support from the fact that in a few instances certain products were considered for a time to be rayless, but further investiga-

tion revealed the existence of slow-moving charged particles arising from them, which, being very weak ionizers, had escaped detection.

The latter hypothesis suggests the possibility that all matter might be undergoing a very slow change in a similar manner, and that the only reason this change has been observed in the so-called radio-active bodies and not in the non-radio-active bodies is that in the case of the former the charged particles are expelled with sufficient violence to ionize the gas, while in the latter case they may be expelled but not with sufficient violence to produce ions. To decide this question experimentally appears to be practically impossible unless some means, other than at present known, of detecting such slow-moving particles be discovered.

147. Summary of Radio-active Elements.—Since the discovery of radio-activity the list of radio-elements has grown rapidly. Owing to the persistent energy of experimenters in this line the list is continually receiving additions, and in all probability there still remain others to be discovered. In fact, during the writing of this book two new radio-elements have been added to the list. The following table contains a summary of all the radio-active elements at present known with some of their distinguishing characteristics. On account of the incomplete state of the subject further experimental investigation and still more accurate determinations will no doubt cause additions and alterations in connection with this table.

The first column gives the elements in the order in which they are transformed from one to the other; the second column shows the period required for the transformation to be half completed, while the third indicates the nature of the rays emitted by each product.

TABLE OF RADIO–ELEMENTS

Radio-Active Products.	Transformation Period.	Nature of Rays Emitted.	Radio-Active Products.	Transformation Period.	Nature of Rays Emitted.
Uranium ↓	5×10^9 years	α	Thorium ↓	10^{10} years	α
Radiouranium ↓	?	?	Mesothorium 1 ↓	5.5 years	Rayless
Uranium X ↓	22 days	β and γ	Mesothorium 2 ↓	6.2 hours	β and γ
Ionium ↓	?	α	Radiothorium ↓	800 days	α
Radium ↓	2000 years	α	Thorium X ↓	3.7 days	α
Emanation ↓	3.75 days	α	Emanation ↓	54 seconds	α
Radium A ↓	3 minutes	α	Thorium A ↓	11 hours	Slow β rays
Radium B ↓	26 minutes	β and γ	Thorium B ↓	1 hour	α
Radium C ↓	19 minutes	α, β, and γ	Thorium C ↓.	?	α, β, and γ
Radium D (Radio-lead) ↓	40 years	Rayless	Thorium D ↓ ?	?	?
Radium E ↓	6 days	Rayless	Actinium ↓	?	Rayless
Radium F ↓	4.5 days	β and γ	Radioactinium ↓	19.5 days	α
Radium G (Polonium) ↓ ?	140 days	α	Actinium X ↓	10 days	α
			Emanation ↓	3.7 seconds	α
			Actinium A ↓	36 minutes	β
			Actinium B ↓	2.15 minutes	α
			Actinium C ↓ ?	5.1 minutes	β and γ

CHAPTER XV.

A SPECIAL METHOD OF ANALYSIS BY ABSORPTION CURVES.

148. In the present chapter a brief account will be given of a special experimental method of radio-active measurement which has been used to great advantage and which has led in some instances to important discoveries.

149. Homogeneous Source of α Rays.—In several important investigations on α rays, especially those involving accurate quantitative determinations of their constants, it is very necessary to have a homogeneous source of α rays. This cannot be obtained from the ordinary radium compounds in equilibrium, for these compounds are complex, the different constituents emitting rays of different velocities. A very convenient source is furnished by the active deposit from the radium emanation. If a fine copper wire be exposed to the radium emanation for about two hours an active deposit, consisting of radium A, B and C, is the result, of which radium B emits no α rays, so that all the α rays come from radium A and C. But the activity of radium A very rapidly decays, reaching half value in three minutes, so that at the end of about fifteen minutes after removal from the emanation radium A has practically disappeared and therefore radium C is the only source of α rays, which thus furnishes a homogeneous source.

Radium C deposited in this manner has other advantages as well. It may be deposited on a very fine wire, and therefore a source of very small dimensions may be used. In addition, the coating of deposit on the wire is so extremely thin that there is no absorption of the rays due to passage through the active material.

There is one slight disadvantage in regard to this source owing to the fact that its activity decays with time. This however is not serious, as the rate of decay has been so carefully

determined and this determination may be repeated in each case simultaneously with the other measurements if necessary, that the rate of decay is known and thus the readings can always be corrected for a constant source.

This source of α rays has been utilized in a number of important determinations, such as the magnetic and electrostatic deflection of the α rays in the determination of the velocity and the value of e/m (see § 110), and the determination of the range in air over which these rays produce ionization, or photographic or phosphorescent action. The change in velocity and the absorption of the α rays in passing through matter has also been determined by using such a source.

150. Theory of Analysis by Absorption Curves.—We have seen that the α rays are absorbed in passing through gases and that it requires only a comparatively few centimeters of air to completely absorb them, that is, they have a definite range in air. The α particle in passing through the gas ionizes it, and as ionization requires energy the energy is obtained at the expense of the kinetic energy of the moving particle, and finally its velocity is reduced below that required to produce ions and complete absorption is the result, as it is not observable after it has lost its power to produce ions. The range of complete absorption will be different for the α rays from different substances, since they are projected with different velocities.

Suppose that a thick layer of a single radio-active element R (Fig. 71) be placed in the bottom of a deep recess in a lead block so as to obtain a definite cone of α rays. Let A, a metal plate, and B, a sheet of wire gauze parallel to A at a fixed distance from it of 2 or 3 mm., form an ionization chamber. The α rays from R come from different depths in the material, and therefore those arising from the lower layers will be absorbed more before they
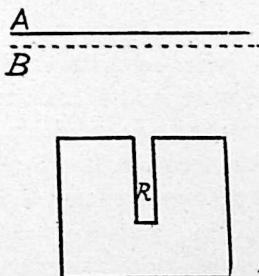
FIG. 71.

emerge into the air than those from the layers nearer the surface. Consequently α rays of velocities extending over a considerable range will emerge at the surface and ionize the air. If the chamber AB be placed above the source at a distance beyond the range of the swiftest particles no ionization will be produced in AB since no rays will reach it with sufficient velocity to ionize. The area of both A and B should be great enough to cover more than the whole cross-section of the cone of rays. If AB is gradually lowered the rays of greatest range will first enter it and produce a small amount of ionization, and on lowering it still farther the rays of next greatest range will reach it and increase the ionization. By continuing to lower AB the ionization will gradually increase, because more and more rays enter it the nearer it is to the source. Consequently, if a curve be plotted showing the relation between ionization and distance from the source it would take the general form of the straight line MN, Fig. 72, where the ordinates represent distance from the source and the abscissæ the ionization. The ionization increases as the source is approached.

If however a thin layer of material be used at R instead of the thick one the rays will be much more nearly homogeneous. The gradual increase will take place over a much shorter range and within a certain distance of the source all the rays will enter AB and the curve will take the form MPR. At the distance corresponding to P all the rays enter AB and therefore the ionization does not increase any more by further approach towards the source.

FIG. 72.

If a thin layer of a complex radio-active body consisting of two or more active elements, from each of which a group of rays arises with initial velocity different from the others, be used as source the curve will be a little more complicated and will take the general form shown in Fig. 73, supposing the
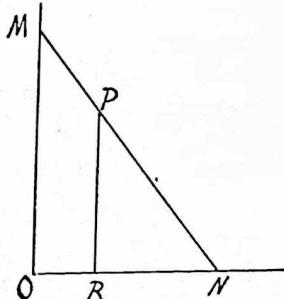
source consists of a mixture of three simple substances. The part *RS* corresponds to the rays from one source which are of greatest range, and if these were the only ones present the curve would continue along the dotted line *SA*. At the distance corresponding to *S* the group of rays from the second source of next greatest range make their appearance in the ionization chamber and constitute the part *ST* which, if there were no more, would continue along *TB*. Similarly the third source corresponds to the part *TV*. This method of investigation furnishes a powerful method of analysis in certain lines, and by its application the presence of some of the radio-elements have been first discovered.
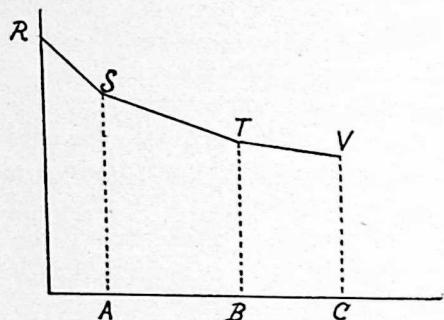
FIG. 73.

151. Experimental Arrangement for Analysis.—The appa-
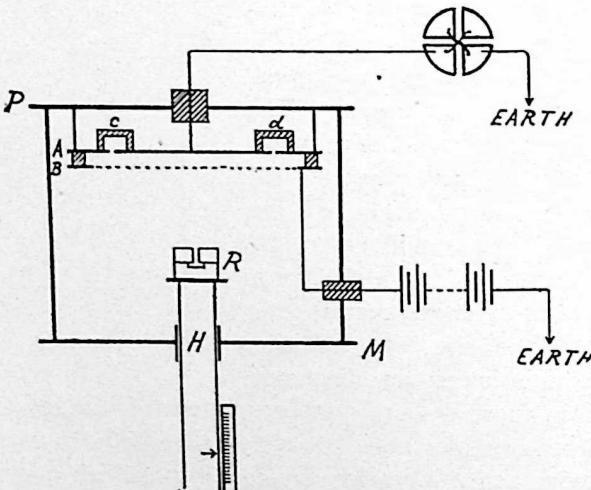
FIG. 74.

ratus shown in Fig. 74 has been found to be suitable

for this type of investigation. *PM* is a metal box about 25 cm. square. *A* is the upper plate of the ionization chamber consisting of a central plate about 12 cm. square surrounded by a guard-ring. The central plate is insulated and supported by the ebonite arches *c* and *d*. *B* is a sheet of wire gauze of fine wire but wide meshes of about 2 or 3 mm. supported and insulated by ebonite blocks, as shown, at a distance of 3 mm. from *A*. This whole system is supported from the cover of the box.

The receptacle *R* for holding the radio-active body consists of a brass block about 3 cm. square made in two sections. The lower half has a shallow recess cut in the center of the upper face, while the upper half has a corresponding central hole of less diameter than the recess in the lower section. The two parts are made to fit together in a fixed relative position. They may be separated and the radio-active body placed in the recess of the lower section and then the upper one placed over it so that the radiations can emerge only through the hole in the upper block. This is supported on an upright *H* which passes through an opening in the bottom of the box, and which may be moved vertically by a screw and the distance of *R* from *A* measured by a scale along the side. The source of rays can thus be placed at any distance from *A* and the ionization in *AB* measured in the usual manner.

Place about 5 milligrams of radium bromide in *R* and measure the saturation current between *A* and *B* for different distances of *R* from *A* over a range of about 8 cm. Plot a curve with distances as ordinates and current as abscissæ. Observe the different straight line sections of the curve showing the complex nature of the source.

Heat a specimen of this radium bromide to drive off its emanation and other products and then redetermine the curve. Observe that it is of a much simpler character than in the former instance, showing that the source is less complex.

Expose a thin copper wire in radium emanation for a couple of hours to obtain an active deposit upon it. Remove the wire and use the radium C as the source of radiation as described in § 149. Using the steady deflection method determine an

experimental curve for current and distance for the radium C. The curve should take the form shown in Fig. 75, which is a specimen curve obtained by actual experiment in an investigation by the author. Since the radium C decays during the time of the observations, the readings must be corrected for the decay of the source. This may be done by bringing the source R back to a fixed position after about every four or five readings and measuring the current for that position, and at the same time observing the time intervals. The rate of decay can thus be observed and the necessary correction made for a constant source.

If a sample of radiothorium is available determine a corresponding curve, using it as the source of rays. It will be found to consist of two distinct parts, showing the complexity of the source. It was by a determination of this very curve for radiothorium that Hahn discovered the previously unknown or unsuspected substance, thorium C.

These experiments all show that the α particles emitted by different radio-active substances have definite ranges over which they will produce ionization and that the ionization stops abruptly at given distances from the source, these distances depending upon the velocity of initial projection.

Instead of detecting the α rays by the ionization produced, their presence may be detected by the scintillations produced on a zinc sulphide screen. Their range of action should be determined by this method and it will be found to be the same as their range of activity as ionizers.
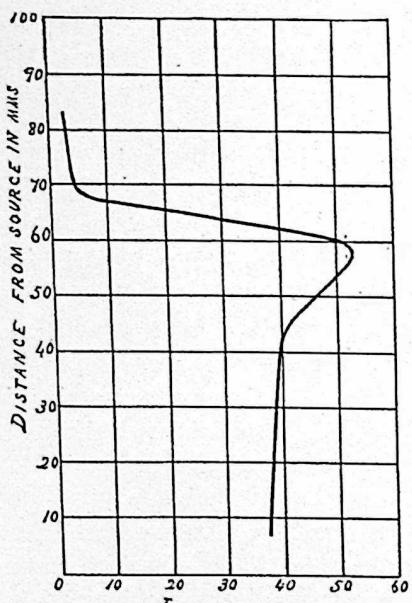
CHAPTER XVI.

RADIO-ACTIVITY OF THE ATMOSPHERE.

152. Loss of Charge in Closed Vessels.—Make an electroscope of the form shown in Fig. 14 of about 500 c.c. in volume. For this purpose a perfectly new one should be made, and do not under any circumstances use one that has been connected in any way whatever with other radio-active measurements. In addition, *every* portion of the material used in its manufacture should be absolutely free from the slightest chance of previous contamination by any radio-active body, and all the measurements which are to follow should be made in a laboratory where no radio-active material has ever been used.

For this purpose it will be found convenient to select a brass tube about 8 cm. diameter and 10 cm. long for the containing vessel. Close the ends by brass plates so as to be air-tight. Thoroughly clean every portion of the surface of the brass with emery paper. Arrange the insulated system as in Fig. 14. Instead of the charging arrangement *F*, attach a very flexible piece of steel watch spring to the lower end of the rod *D*, as shown in (*a*), Fig. 14, and bend it into a convenient shape so that it will not touch the sulphur head and will also hang clear of the lower rod *H*, but so that the lower end of the spring may be brought temporarily in contact with *H*, either by bringing a strong magnet near it or by tilting the whole electroscope and slightly jarring it. This arrangement will allow the instrument to be made gas-tight.

Set this electroscope up in a room perfectly free from the slightest contamination from any radio-active material and fill it with perfectly dry and dust-free air. Charge up the gold leaf system to about 200 volts and observe any slow movement of the gold leaf in the usual way by a reading microscope with micrometer eye-piece. During these readings keep the rod *D* permanently connected to a battery of 200 volts.

Observe that the potential of the gold leaf system slowly decreases. This decrease cannot be due to imperfect insulation of the sulphur bead, for since D is maintained at a constant potential as high or higher than the gold leaf any leakage across the sulphur would take place from D to the gold leaf instead of the other way and tend to maintain the potential of the gold leaf instead of allowing it to decrease. The leakage must then be through the air and must therefore be due to the presence of ions in the air.

Determine the electrostatic capacity of the electroscope and measure the current per second corresponding to this slow leak, and, assuming the charge on the ion (§ 81), calculate the number of ions produced in the air per second in the volume contained in the electroscope and then determine the number per cubic centimeter.   -

A great variety of experiments of this nature have been performed by a number of observers and it is found that there are always a few ions present in the air or any other gas, but the number varies somewhat under different conditions. Gases thus always possess at least a small amount of conductivity. Every electroscope has therefore what is usually termed its *natural rate of leak,* and in using the electroscope for making radio-active measurements this natural rate of leak must always be independently determined and subtracted from the total rate of leak.

153. **Effect of Conditions on the Natural Leak.**—Measure this natural rate of leak for the air at different pressures in the electroscope. Note that it is approximately proportional to the pressure. Measure also this natural conductivity for various gases at the same pressure and note that the greater the density the greater the conductivity, although it is not quite proportional in all cases.

If the electroscope be surrounded underneath and on all sides by lead sheets about 5 cm. thick the natural rate of leak will be diminished by quite a large percentage, but a further increase in thickness of the lead will cause no further diminution in the conductivity. This indicates that part at least of the natural

conductivity is due to a very penetrating radiation of some sort from the earth and air.

154. Excited Activity in the Atmosphere.—Suspend a copper wire, 12 or 14 meters long, in the open air and keep it charged to a high negative potential of about 10,000 volts for an hour or two by connecting it to the negative pole of a Wimshurst machine. Then remove it and quickly wind it back and forth on an open rectangular framework about 80 cm. long and 20 cm. wide. Suspend and insulate this frame in the centre of a metal cylinder of about 25 cm. diameter and 100 cm. long. Test in the usual manner by means of a sensitive electrometer, for an ionization current between the cylinder and this wire acting as the central electrode. The wire will be found to be radio-active and to act in all respects like a wire made active by exposure to an emanation. The activity of the wire can be partially removed by rubbing and by dipping the wire in acid solution. It also decays with time, falling to half value in about three quarters of an hour. Obtain a decay curve for it in the usual manner.

Since under no other circumstances has an active deposit of this nature been obtained except in the presence of an emanation it appears from these results that there must be an emanation of some sort in the atmosphere. This question has been investigated by different observers using different methods, and it has been shown that both radium and thorium emanations are present in the atmosphere. The amount of these emanations in the atmosphere is different in different localities. The excited activity obtained on a negatively charged wire in the air is due to a mixture of the active deposits from both radium and thorium, but on account of the very rapid decay of thorium emanation most of the activity arises from the radium emanation. It is not surprising that these emanations should be found in the atmosphere, for since both radium and thorium are known to be distributed among different deposits throughout the earth the emanations must be continually diffusing into the atmosphere in small quantities. The presence of this radio-active matter in the air will explain

to some extent at least the natural conductivity of the atmosphere.

If freshly fallen snow or rain be collected and quickly evaporated to dryness in a platinum vessel the residue will be found to be radio-active if tested by an electroscope. This active residue acts in a manner similar to that of the active deposit obtained on the negatively charged wire exposed to the atmosphere. The rate of decay of the active residue from snow or rain is a little more rapid than the rate of decay of the active deposit on the wire. The falling rain or snow apparently carries down this active matter from the atmosphere and it remains behind after evaporation of the rain or snow.

Meteorological conditions are observed to influence the amount of excited activity obtainable from the atmosphere to a considerable extent. The amount of excited activity is subject to great variations. The activity is greater at the temperatures below 0° C. than at those above 0° C. The lowering of the barometric pressure causes an increase in the amount of excited activity.

155. **Present State of the Subject of Atmospheric Ionization.**—The whole subject of the radio-activity of the atmosphere is a wide one, as there is such a variety of existing conditions to be taken into account. It is influenced by meteorological conditions, by the presence of any radio-active deposits in the neighborhood and by particular local conditions. There are also different kinds of radiations which unite to produce this conductivity of the air, some of which are very easily absorbed and others of which are extremely penetrating. The conductivity is so complex and also subject to such fluctuations that it is difficult to obtain perfectly definite results on which a satisfactory general explanation may be based. A great deal of work has been done on this subject, but there still remains a considerable amount of very careful investigation to be carried out in order to place the subject on a satisfactory basis.

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