A NEW METHOD OF POSITIVE RAY ANALYSIS.

BY A. J. DEMPSTER.

THE analysis of positive rays is based on the determination of the ratio of the charge to the mass of various constituents. The corresponding measurement for the negative corpuscle has however been carried to a much greater degree of accuracy by means of methods involving the magnetic deflection of the rays through large angles, and the refocusing of rays which make slightly varying angles with each other. Apart from the accuracy of the measurement, there is also in these methods a great resolution between slightly different speeds; thus Rutherford and Robinson[1] have separated distinct groups of β rays from RaC which differ by 2 per cent. in energy; also the photographs given by Classen[2] for electrons show such sharpness that if electrons had masses differing by as little as 1 in 100, the various groups would be separated. With positive rays the slit method used by Richardson[3] is suitable for weak sources and allows a fairly exact measurement of a mean molecular weight, but the curves given in the above paper show that the power of separating different elements is very small. The method used by J. J. Thomson is capable of comparatively great resolving power, elements being sharply separated which differ in molecular weight by 1 in 16,[4] but this is obtained only with a great loss in intensity. The method developed in the present experiments was expected to give great intensity with moderate resolution. It was found that the method could also be developed to give a very great resolving power among the elements.

The method is essentially identical with that used by Classen in his determination of e/m for electrons. The charged particles from some source fall through a definite potential difference. A narrow bundle is separated out by a slit and is bent into a semicircle by a strong magnetic field; the rays then pass through a second slit and fall on a plate connected to an electrometer. The potential difference (P.D.), magnetic field

[1] Phil., May 26, p. 725, 1913.

[2] Jahrb. d. Hamburg Wiss. Anst., Beiheft, 1907.

[3] Phil., May 16, p. 757, 1908; The Emission of Electricity from Hot Bodies, p. 196.

[4] Nature, 86, p. 468, 1911.

(H_0), and radius of curvature (r) determine the ratio of the charge to the mass of the particles by the usual formula

$$\frac{e}{m} = \frac{2 \cdot PD}{H_0^2 r^2}.$$

The apparatus consisted of the glass tube G, where the positive particles fell through a definite potential difference, and the analyzing chamber A, in which a strong magnetic field was produced between two semicircular iron plates 2.8 cm. thick and 13 cm. in diameter. The iron plates were soldered into half of a heavy brass tube B so as to leave a passage or slot 4 mm. wide between the plates. A plate of brass on top C closed this slot except for three openings into which short brass tubes were soldered. The glass tube G fitted into the first opening and a tube for exhausting into the second. The electrometer connection passed to a receiving plate through an ebonite plug E which formed a ground conical joint with the third brass tube. The two openings for the rays had adjustable slits S_1, S_2, and a screen D was introduced into the analyzing chamber to prevent reflected rays getting into the second slit. The whole was placed between the poles of a powerful electromagnet. The strength of the magnetic field and the manner in which it fell off above the entrance was determined with a test coil. The throws obtained on removing the coil rapidly were compared with the throws obtained from two coils whose mutual inductance was known, when the current through one was broken. In this way a curve was drawn connecting the field strength and the current through the electromagnet. The current was always reversed slowly several times before taking a reading. The field strength was the same over the whole area of the plates to within one per cent. The rays were obtained either by heating salts on platinum strips, as in Richardson's experiments, or by bombarding salts with electrons; in the latter case the salts were either heated by the bombardment or were heated independently while being bombarded.

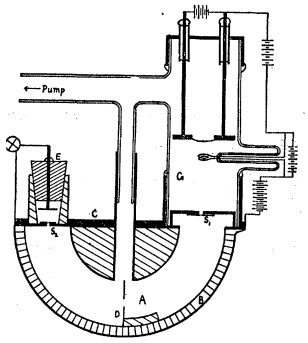

Fig. 1.

It might be thought from the elaborate precautions taken in the experiments by Wien and Thompson to prevent the discharge tube being influenced by the magnetic field used for deflecting the rays, that great difficulty would be experienced in introducing the rays properly into a sufficiently strong magnetic field, and in drawing conclusions from

the deflection observed. But such is not the case. The equations for the motion of a charged particle in a longitudinal electric field (PD/a) parallel to the z-axis, and a transverse magnetic field $H(z)$ parallel to the x-axis are

$$\frac{d^2z}{dt^2} = \frac{e}{m} \cdot \frac{PD}{a}; \qquad \frac{d^2y}{dt^2} = \frac{e}{m} H \frac{dz}{dt}.$$

The integration of the first gives

$$\frac{dz}{dt} = \sqrt{\frac{2e \cdot PD}{m \cdot a}}\, z^{1/2},$$

and using this in the second we get on integrating

$$\frac{dy}{dz} = \sqrt{\frac{e}{m} \cdot \frac{a}{2PD}}\, z^{-1/2} \int_0^z H(z)dz.$$

$$\therefore \quad \left(\frac{dy}{dz}\right)_a = \sqrt{\frac{e}{m}\frac{1}{2PD}} \cdot \int_0^a H(z)dz = \frac{1}{rH_0} \int_0^a H(z)dz. \qquad (1)$$

If we put

$$z^{-1/2} \int_0^z H(z)dz = K(z)$$

$$y_a = \frac{a}{H_0 r} \int_0^a K(z)dz.$$

(1) also applies to the case of particles moving in a magnetic field alone. The magnetic field was reduced to zero at the place of origin of the rays by the use of a secondary electromagnet, and the values of the above integrals were observed and calculated by means of a coil wound on a long rectangular frame. If the first slit were placed directly at the entrance to the 4 mm. slot, it was found that the rays would be deflected a distance $y_a = .96$ mm. and through an angle whose tangent $(dy/dz)_a = 1/9.3$. This might be sufficient to destroy the refocusing and to make uncertain the value of r in the equation

$$\frac{m}{e} = \frac{H_0^2 r^2}{2 \cdot PD}.$$

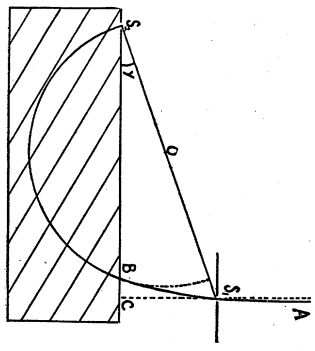

Fig. 2.

These difficulties may however be completely avoided by the simple device of moving the entrance slit out in front of the iron plates. Let the shaded portion in Fig. 2 represent the iron plates, and S_1S_2 the two slits where the distance S_1B is much exaggerated. The geometrical

condition for refocusing is that S_1OS_2 should lie on a straight line. We therefore wish that the figure as drawn should apply to the rays. For this we must have $\gamma = \alpha + \beta$, where α = angle of deflection in AS_1 and β = angle of deflection in S_1B. That is, if $S_1C = b$,

$$\frac{b}{2r} = \frac{1}{H_0 r}\int_A^{S_1} H(z)dz + \frac{1}{H_0 r}\int_{S_1}^{B} H(z)dz$$

or

$$b = \frac{2}{H_0}\int_A^B H(z)dz.$$

This value was calculated to be .93 cm. and the slit S_1 was placed at that distance in front of the iron plates. The distance BC was calculated to be .25 mm. The correct radius of curvature is very closely $(S_1S_2 - BC)/2$ to which $(S_1S_2)/2$ is a sufficient approximation. A high vacuum was obtained by a mercury vapor pump, which acted in connection with a Gaede rotary mercury pump. Mercury vapor must be kept away from the apparatus at all times by the use of liquid air, for in a very short time sufficient will diffuse over and condense on the brass to prevent a high vacuum being obtained.

If the charged particles all fall through the same potential difference, the most reliable method for analyzing the rays is to keep the magnetic field constant, and vary the potential difference so as to bring successive elements onto the slit, for in the fundamental equation and in (1), m and PD occur only in the product $m \cdot PD$, and the rays will therefore follow identical paths for $m \cdot PD$ = const. This would allow the comparison of molecular weights with the accuracy of a potential measurement; and if a molecular weight is known the original magnetic field determinations can be corrected. If, however, charged surface layers are formed on the salts from which the ions start, the above method would not be reliable. It was found that in practically all cases the calculated molecular weights came out very close to the chemical molecular weights, so that no assumptions of surface layers comparable to the potentials used, and only small corrections to the magnetic field determinations were necessary. An exception occurred with very weak magnetic fields, but this is at present ascribed to the difficulty in reproducing the magnetic fields with very weak currents.

RESOLVING POWER.

If the rays were uniformly distributed over the entrance slit and the refocusing perfect, the curve obtained for the charge as the potential or field strength is varied to bring various parts of the bundle on the exit slit, would be of the form given in Fig. 3. Let S be the width of the slits

and h_1h_2 represent the abscissæ where the curve is half its maximum value. $S = h_1h_2$ if the abscissæ represent distances. In order to see what change in m is necessary to produce a displacement h_1h_2, we have from the formula

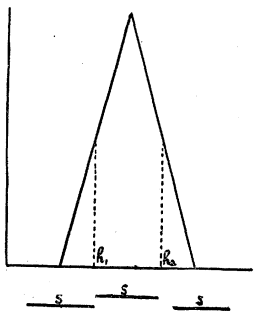

Fig. 3.

$$m = \frac{eH_0^2r^2}{2 \cdot PD}$$

$$\frac{\Delta m}{m} = \frac{2\Delta r}{r} = \frac{2\Delta d}{d} = \frac{2S}{d},$$

where $d = 2r$. This may be called the limit of resolution, and if two molecular weights differ by this amount, the point h_1 of the one coincides with the point h_2 of the other. In the apparatus $d = 10$ cm., so that for slits $\frac{1}{2}$ mm. wide we should have

$$\frac{\Delta m}{m} = \frac{1}{100}.$$

Preliminary Experiments.

The first experiments were made with ions obtained by heating a mixture of sodium phosphate and calcium oxide on a platinum strip. Several widely separated groups of rays were observed with slits about 2 mm. wide. The molecular weights agreed approximately with Na and K for the strongest positive, and with O_3 and CaO for the strongest negative lines. The positive emission changed gradually with heating, from being entirely potassium to being mostly sodium.

In another experiment manganous chloride ($MnCl_2$) was heated and the negative emission was observed. Three distinct molecular weights were observed which agreed approximately with negatively charged oxygen molecules, manganese with a double negative charge, and manganous oxide with a single charge.

Positive Ions from Aluminium Phosphate.

The positive ions obtained from heated aluminium phosphate have been used by many experimenters. These ions were analyzed and found to consist usually of sodium and potassium, although on one occasion after standing overnight, the emission was at first entirely hydrogen atoms. This wore off in a few minutes and the emission became sodium and potassium. At first the potassium was very much stronger than the sodium, but after heating some time it died off and became much weaker. The emission was examined only at low temperatures as with increasing temperature the currents soon became inconveniently large.

TABLE I.

P.D.	*M.*	Current.	P.D.	*M.*	Current.
679	22.79	3.8	705	21.93	117.
685	22.57	17.8	711	21.74	80.
689	22.44	43.5	715	21.62	58.8
693	22.31	90.9	719	21.50	20.8
699	22.12	133	723	21.39	3.3

As an example the figures in Table I. give the actual readings in one measurement of the sodium line. The entrance slit was 1.9 mm. wide, the exit slit 1.65 mm. wide and a screen 3.3 mm. wide was placed half way around the semicircle. The current through the electromagnet was kept constant at .8 ampere giving a magnetic field of 3,580 gausses according to the curve drawn from the original determinations. The potential difference (*PD*) which was obtained from banks of small storage cells is given in volts, and the molecular weight $M = m/m_1$, is calculated from

$$m = \frac{eH^2_0 r^2}{2V}$$

and

$$m_1 = \frac{e}{9650} \; ; r = 5 \text{ cm.}, e = 1{,}591 \times 10^{-20}.$$

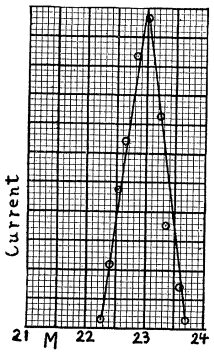

Fig. 4.

The current given was observed with the electrometer for the different potentials between the heated salt and the slit. The maximum comes at 22.1, but, as there can be no doubt that this line really is sodium, we can explain the difference as due to the value of the magnetic field being 2 per cent. too low. The difference is probably not due to the ions falling through less potential difference than the total applied, since, with other values of the magnetic field, values of M very close to 23 were obtained. The curve, Fig. 4, is drawn with the magnetic field corrected to bring the maximum at 23, and shows an approximation to the theoretical form of Fig. 3. The limit of resolution should be between

$$\frac{\Delta m}{m} = \frac{2 \times 1.65}{100} = .033$$

and

$$\frac{2 \times 1.9}{100} = .038,$$

whereas that observed is .7/23 = .028. The form of the curve shows that the influence of the small amount of gas remaining is very slight.

Fig. 5 gives the curves for sodium and potassium under slightly poorer vacuum conditions, both taken while the magnetic field was held constant at 5,200 gauss. The maximum for sodium was obtained with 1,433 volts and for potassium with 845 volts. The ratio is almost exactly 39 to 23. The curve is drawn with a slightly corrected magnetic field so as to bring the sodium maximum from 22.8 to 23.00. The potassium ordinates are multiplied by 50 so that the sodium in this case was about 90 times as strong as the potassium. These curves indicate that the charged particles actually fall through the total potential difference.

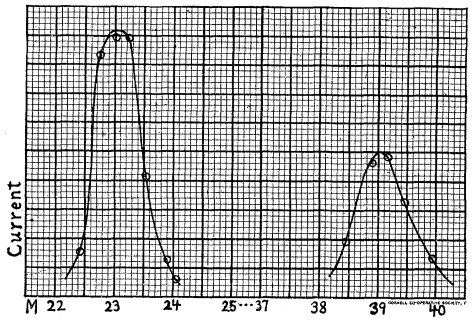

Fig. 5.

The emission starts rather suddenly as the temperature of the strip is raised, in the manner discussed by Richardson; but it was observed that the potassium emission commences at a lower temperature than the sodium. As the temperature was lowered the sodium disappeared while the potassium was still strong. The Table II. gives the currents observed

TABLE II.

K.	Na.
1.9	0
38.4	1.4
62.5	5
71.4	19
208	91
52.6	2000

for each as the temperature was raised by increasing the heating current. The potassium is much stronger than the sodium at first but at higher temperatures the sodium becomes the stronger.

No great difficulty is expected in extending the investigation to all the substances found by Richardson and others to emit positive or negative ions on being heated. With weak sources it will be necessary to widen the slits and be content with less resolution.

Positive Ions from Electron Bombardment.

It was thought that the bombardment of salts by electrons might break up the chemical compounds and give rise to many positive ions. At first a Wehnelt cathode was used; the ions formed passed beside the cathode (Fig. 1) and were then accelerated by a large potential difference. Aluminium phosphate on a piece of platinum foil was first bombarded. The intensity of the rays increased very rapidly with a slight increase in the amount or energy of the bombarding electrons, indicating that the salt needs to be heated to a certain degree before the ions are separated. Although the aluminium phosphate was chemically pure, the rays obtained under the bombardment of 128 volt electrons were very complex; the following ions were observed besides a couple of unresolved groups; H_1, H_2, Li (weak), O_1 (strong), Na (strong), O_3 (?) (weak), $M = 62$ (weak, possibly Na_2O), $M = 67$ (strong, possibly $H_3PO_2 = 66$), $M = 76$ (strong), $M = 86$ (weak, possibly Rb = 85.5), $M = 112$ (strong, possibly $P_2O_3 = 110$).

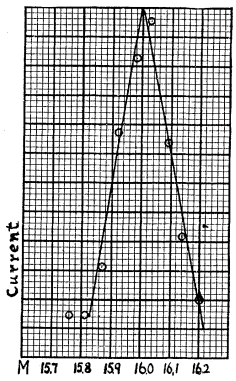

Fig. 6.

The experiments indicated the convenience of the method of obtaining positive rays and opened up an interesting field for investigation.

The experiments were however first directed towards testing out the possibility of obtaining still greater resolving power. The curve in Fig. 6 for oxygen from the bombardment of aluminium phosphate was obtained with $\frac{1}{2}$ mm. slits and two screens with 2 mm. openings placed in the path of the rays. Table III. gives the actual observations. The magnetic field has been corrected so as to bring the maximum from 16.73 to 16. The theoretical resolution is

Table III.

P.D.	*M.*	Current.	P.D.	*M.*	Current.
1,758	15.76	7.3	1,728	16.03	58
1,752	15.81	7.3	1,722	16.09	37
1,746	15.87	15.6	1,716	16.14	21
1,740	15.92	38.6	1,710	16.20	10
1,734	15.98	51			

$$\frac{\Delta m}{m} = \frac{2 \times .5}{100} = .01;$$

the observed is .2/16 = .012. From the bombardment of aluminium phosphate to which a little lithium chloride and sodium chloride had been added strong bundles of hydrogen atoms and hydrogen molecules were obtained. With slits $\frac{1}{2}$ mm. in width and a screen with an opening 4 mm. in width placed in the path of the rays, the curves in Fig. 7 were

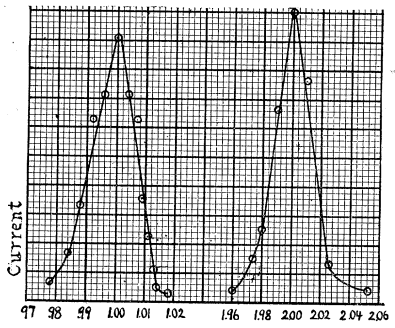

Fig. 7.

obtained. The magnetic field has been corrected to shift the maximum from .92 to 1.00 and from 1.77 to 2.00. The actual observations for the first curve are given in Table 4. The limits of resolution observed are .015 and .017.

It is generally assumed that the hydrogen and oxygen atoms are perfectly homogeneous so that the object in developing the above resolving power was to apply it to elements whose homogeneity has recently been considered a questionable matter. In a recent lecture Professor Soddy says[1]:

TABLE IV.

Volts.	*M.*	Current.	Volts.	*M.*	Current.
1,470	1.018	2.8	1,496	1.000	91
1,478	1.013	11.1	1,502	.9961	71.4
1,480	1.011	22.2	1,508	.9922	62.5
1,482	1.009	35.7	1,514	.9883	33.4
1,486	1.006	62.5	1,520	.9845	16.7
1,490	1.004	71.4	1,530	.9780	6.7

"When, among the light elements, we come across a clear case of large departure from an integral value, such as magnesium 24.32 and chlorine 35.46, we may reasonably suspect the elements to be a mixture of isotopes." With the resolving power in the above examples this question can obviously be definitely decided, for, if the element is really homo-

[1] Nature, 1917 also Scientific Monthly, p. 516, Dec. 1917. See also Fajans, Phys. Zeit., 1916.

geneous, the curve will lie entirely between two integral values, and if it is a mixture of elements differing by integers, the molecules will be completely separated. The only experimental difficulty is to get the rays, and this is the matter now under investigation. Magnesium has been tried by bombarding it with electrons from a tungsten filament while it was being heated by a platinum strip around which it was wrapped. With slits 1.9 mm. and 1.65 mm. in width intense rays of oxygen molecules (calculated 32.01) were obtained and after heating for some time rays of nitrogen or carbon monoxide (28.00) appeared. Rays that are probably chlorine have been obtained from the bombardment of a heated anode of aluminium phosphate, potassium chloride and potassium iodide with electrons from a tungsten filament. The apparatus was however at the time slightly contaminated with mercury, and the curves were so broadened that no conclusion could be drawn. A crystal of KI was bombarded and found to give strong H_1 and H_2 rays; no H_3 or helium was observed.

The experiments described above are concerned chiefly with the development of the method, and they are published now only because the writer expects to be engaged in other duties for some time.

The writer wishes to express his appreciation of the kindness of Professor Michelson and Professor Millikan in placing the equipment of the laboratory at his disposal and in rendering every possible assistance.

SUMMARY.

An apparatus for analyzing positively or negatively charged particles is described. Examples are given of the analysis of the ions from heated salts and of the positive rays obtained by bombarding various substances with electrons. The high resolving power obtainable with the method is also illustrated.

RYERSON PHYSICAL LABORATORY,
CHICAGO,
October 20, 1917.