XXV. Charge carried by the α and β rays of radium

E. Rutherford F.R.S.

To cite this article: E. Rutherford F.R.S. (1905) XXV. Charge carried by the α and β rays of radium, Philosophical Magazine Series 6, 10:56, 193-208, DOI: [10.1080/14786440509463363](https://doi.org/10.1080/14786440509463363)

To link to this article: <http://dx.doi.org/10.1080/14786440509463363>

Published online: 16 Apr 2009.

Submit your article to this journal [↗](#)

Article views: 8

View related articles [↗](#)

Citing articles: 10 View citing articles [↗](#)

THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[SIXTH SERIES.]

AUGUST 1905.

XXV. *Charge carried by the α and β Rays of Radium.* By
E. RUTHERFORD, F.R.S., *Macdonald Professor of Physics,*
*McGill University, Montreal**.

IN the Bakerian Lecture (Phil. Trans. A 204. pp. 169–219, 1904), I gave an account of some experiments made in order to measure the charge carried by the α rays, with a view of determining the number of α particles shot out per second from a given mass of radium. The method employed is clearly shown in fig. 1. A known small quantity of pure

Fig. 1.

radium bromide was dissolved in water and the solution spread uniformly on a metal plate A, and then evaporated to dryness. The process of solution and evaporation liberates the radium emanation and about three hours afterwards

* Communicated by the Author. A brief account of the results included in this paper was published in a letter to 'Nature,' March 2, 1905.
Phil. Mag. S. 6. Vol. 10. No. 56. Aug. 1905. O

the excited activity practically disappears, and the activity, measured by the α rays, is reduced to one quarter of its equilibrium value. Experiments were made with the radium as nearly as possible at this minimum activity in order to avoid possible complications due to the presence of β rays. The latter have almost completely disappeared about three hours after the emanation is removed. The β activity is gradually recovered, rising to half its maximum value in about four days.

A second insulated plate B was placed parallel to the lower plate and a few millimetres distant from it. The plates were insulated in a brass vessel which could be exhausted to a high vacuum by means of a mercury pump. The lower plate A was connected with one pole of a battery, the other pole of which was connected to earth. The current passing between the two plates was measured by a Dolezalek electrometer with a suitable capacity in parallel.

If the α rays carry with them a positive charge, this will be communicated to the upper plate in which they are absorbed. At ordinary pressures of the air, however, the amount of ionization produced by the α particles in their passage through the gas is so large that this charge is rapidly dissipated. It is necessary to work at a very low pressure of the gas, in order to reduce the ionization to a very small value. Under such conditions, it was to be expected that the upper plate would acquire a positive charge. A very different result, however, was observed: on diminishing the pressure of the gas, the current between the plates decreased directly as the pressure, but finally reached a limiting value, corresponding to about 1/1000 of the value at atmospheric pressure. This current was about the same whether the lower plate was charged positively or negatively, and, although an extremely high vacuum was produced, it was not found possible to further reduce its value. This minimum current was not much altered when hydrogen was present in the vessel instead of air.

No certain evidence that the α particles carried a charge could be obtained. It was suggested that the failure to detect this charge might be due to the presence of a number of slow moving electrons, liberated from the plates by the action of the rays.

The following explanation (*loc. cit.*) was given:—

“The apparent absence of charge on the α particles would be explained if an equal number of negatively charged particles, or electrons, were expelled at the same time with a slow velocity. If the electrons had about the same penetrating power as the α particles, it would be difficult to detect their

presence by the electric method, as the ionization produced by the α particles would probably mask that produced by the electrons. The electron should be readily deflected in a magnetic field, and experiments are at present in progress to examine whether the α rays show any trace of positive charge when the rays are exposed to a strong magnetic field."

If a strong magnetic field is applied parallel to the plane of the plates, any slow moving electrons, which escape from the plates, will describe curved paths and return to the plates from which they set out.

Owing to work in other directions, experiments of this character were not begun till November 1904. The apparatus of fig. 1 was placed between the pole-pieces of a large electromagnet, when a striking alteration of the values of the current between the two plates was observed. The currents in both directions were much reduced in value, and the upper plate was found to gain a positive charge, whether the lower plate was charged positively or negatively.

While these experiments were in progress, an abstract of a paper by Professor J. J. Thomson (Proc. Camb. Phil. Soc. Nov. 14, 1904) appeared in 'Nature' (Dec. 15, 1904). In this an account was given of some experiments made with a view of detecting the positive charge carried by the α rays. A plate of radio-tellurium, which emits only α rays, was used. It was found that a number of slow moving electrons were emitted from the active plate, which could readily be bent by a magnetic field. I did not receive a copy of the paper itself until my experiments were completed, and was not aware until after a publication of my results in 'Nature' (March 2, 1905) that Prof. Thomson had previously succeeded in detecting the positive charge carried by the α rays.

As the method employed by J. J. Thomson is especially well suited to show the presence of the electrons expelled with the α particles, a brief account will be given of his experiments. A plate of radio-tellurium was placed in a vacuum-tube 3 cms. away from a metal plate connected with a gold-leaf electroscope. When a very good vacuum was obtained, the electroscope was observed to leak very rapidly if positively charged, and very slowly if negatively. The positive leak was at least 100 times that of the negative. This result indicated that the plate of radio-tellurium expelled a number of slow moving electrons, which gave up their charge to the electroscope. This was confirmed by placing the apparatus in a strong magnetic field. The positive leak was almost stopped, showing that the electrons had been bent away by the action of the magnetic field. The small negative

leak without a magnetic field shows that the electrons are projected with such slight velocity that they cannot travel against the electric field. In a later experiment, where the plates were closer together, it was found that the electroscope gained a positive charge in a strong magnetic field, proving that the α rays carried a positive charge.

The experimental method used by the writer was not so much for the purpose of detecting the charge carried by the α rays, as to measure this charge and so deduce the number of α particles expelled from a known quantity of radium. The use of radio-tellurium as a source of α rays is very advantageous, as the β rays are altogether absent. It has been shown, however, that in the case of radium the disturbance due to the β rays can be avoided by using radium at its minimum activity.

An account will now be given of the details of the experiments. 0.484 milligram of radium bromide was taken, dissolved in water, and the solution evaporated uniformly on a polished aluminium plate, about 20 sq. cms. in area. This amount of radium bromide was not directly weighed, but determined by comparison of the γ ray effect in an electroscope with that produced by 23.7 milligrams of radium bromide. The latter had previously been used in experiments to determine the heating effect of radium, and gave out heat at a slightly greater rate than 100 gram-calories per gram per hour. The radium bromide was thus probably pure.

Assuming that the radium was uniformly distributed on the plate, the weight of radium bromide per sq. cm. of surface was 2.4×10^{-5} grams. This film of radium was so thin that only a very small fraction of the α particles shot out from the surface was absorbed in the radium itself. This is seen to be the case, when it is remembered that half of the α particles emitted by radium are stopped by about .0004 cm. of aluminium, that is, by a weight of aluminium per unit area of about .001 gram. Assuming that the absorption is proportional to density, only a few per cent. of the rays can have been absorbed by the radium itself.

The saturation current due to this deposit of radium at its minimum activity was measured between plates 3.5 cms. apart by means of a high-resistance galvanometer. The current observed was 8.4×10^{-8} amperes.

A second set of experiments were made with a glass instead of an aluminium plate. The deposit of radium was covered with a layer of aluminium-foil .00034 cm. thick. The saturation current, observed as in the case of the aluminium plate, corresponded to 3.3×10^{-8} amperes. From this, it was concluded that the number of α particles issuing through the

aluminium-foil corresponded to about 0.19 milligram of radium bromide. It was thought possible that some of the radium might be absorbed in the pores of the aluminium plate, and it was for this reason that a set of experiments was made with a glass plate. The agreement of the results, however, obtained with the two plates indicate that such an effect, if it exists, is small.

One of these radium-coated plates was placed in the vacuum-vessel D in the position of the plate A.

With the view of reducing as far as possible the number of electrons emitted by the impact of the α particles on the absorbing plate, the α particles were shot into a rectangular copper vessel BC, the bottom of which was covered with a layer of aluminium-foil .00034 cm. in thickness. Most of the α particles passed through this aluminium-foil, and were stopped by the metal walls of the vessel.

The brass vessel D was exhausted by means of a mercury pump to a very low pressure. In later experiments, it was found that a low vacuum could be more easily produced by Dewar's method of absorption of the residual gas by charcoal. A side tube, containing coconut charcoal immersed in liquid air, was connected to the vessel D. The air was first partially exhausted by means of a mercury pump, the coconut charcoal being heated to drive off the absorbed gases. This method was found to be very convenient to keep a good vacuum without the necessity of continuous pumping. The apparatus was placed between the pole-pieces of a large electro-magnet, so that the field was parallel to the plane of the plates AB. The following table gives the numbers obtained for the current, when the lower plate was charged positively or negatively, and when the magnetic field was on or off:—

Potential of lower plate.	Current in arbitrary units.	
	Without magnetic field.	With magnetic field.
0		+ 36
+ 2 volts.	+ 2.0	+ 46
- 2 „	- 2.5	+ 33
		} .395
+ 4 „	+ 2.8	+ 47
- 4 „	- 3.5	+ 35
		} .41
+ 8 „	+ 3.1	+ 56
- 8 „	- 4.0	+ 31
		} .435
+ 84	+ 3.5	+ 77
- 84	- 5.2	+ 24
		} .505

The above numbers refer to the radium-coated glass plate.

When once the magnetic field had attained a certain value a considerable increase in its strength did not affect the magnitude of the current observed. This showed that the field was strong enough to bend back all the electrons and to prevent them reaching the opposite plate. The field was not sufficiently strong to appreciably deflect the α particles themselves.

The magnitude of the charge carried by the α particles can readily be deduced. Let i_0 be the current due to the ionization of the residual gas between the plates. A very small E.M.F. is required to produce saturation at such a low pressure, and this current should be equal in magnitude but opposite in sign when the potential is reversed. Let i_1 be the charge per second communicated to the upper electrode when the lower plate is charged positively, and i_2 the value when charged negatively. Let n be the number of α particles, carrying a charge e , projected per second into the upper plate. Then

$$i_1 = i_0 + ne$$

$$i_2 = -i_0 + ne.$$

Adding

$$ne = \frac{i_1 + i_2}{2}.$$

Now in the third column of the table above, it is seen that the values of $\frac{i_1 + i_2}{2}$ are .395, .41, .435 for 2, 4, and 8 volts respectively. The numbers are thus in fairly good agreement. The charge communicated to the upper plate when the lower plate is earthed, is, as we should expect, slightly less than that calculated from the mean of the two currents, since the ionization of the residual gas tends to dissipate it as soon as the potential of the upper plates commences to rise.

It will be observed that the current between the plates before a magnetic field was applied was greater when the lower plate was negative, and for the potential difference of 4 volts was about 9 times the current due to the α particles alone.

A very different result, however, was observed when the radium-coated aluminium plate was used. In this case, the film of radium was not covered with aluminium-foil.

Voltage.	Without magnetic field.	With magnetic field.
+ 8 volts.	6.0	1.22
- 8 ,,	14.0	.03
		} .62

The negative current was about twice as great as the positive, and over twenty times as great as the current carried by the α particles alone.

A very similar result was observed when the upper electrode BC was replaced by a thick brass plate, fixed at a distance of about 2 mms. from the lower plate. We must thus conclude that the escape of electrons from the lower electrode was considerably reduced by placing a layer of aluminium-foil over the radium. The results obtained in the different experiments were fairly concordant.

The current due to the charge carried by the α particles was not small, and the electrometer-needle moved at a convenient rate when a capacity of $\cdot 0024$ microfarad was added to the system. For example, using the aluminium plate as a source of rays, the mean value of ne was found to be $9\cdot 8 \times 10^{-13}$ ampere.

Assuming that each α particle carries the same charge as an ion, viz. $3\cdot 4 \times 10^{-10}$ electrostatic units, or $1\cdot 13 \times 10^{-19}$ coulombs, the number of α particles projected per second into the upper plate was $8\cdot 7 \times 10^6$. This is the number from $\cdot 484$ milligram of radium bromide; and remembering that half of the α particles projected from the radium are absorbed in the lower plate, it can be readily deduced that the total number of α particles expelled per second from 1 gram of radium bromide at its minimum activity is $3\cdot 6 \times 10^{10}$.

The corresponding number obtained for the $\cdot 19$ milligram of radium bromide on a glass plate was $3\cdot 36 \times 10^{10}$, and for the $\cdot 484$ milligram, when the upper plate B was of brass, $3\cdot 96 \times 10^{10}$. The mean of these three determinations is $3\cdot 6 \times 10^{10}$, and this may be taken as the probable value.

Assuming the composition of the compound employed as RaBr_2 , it follows that the total number of α particles expelled per second from 1 gram of radium at its minimum activity is $6\cdot 2 \times 10^{10}$. Now the α ray activity of radium in radioactive equilibrium is four times this minimum value, and includes three products, viz. the emanation, radium A, and radium C, which emit α rays. We may thus conclude that the total number of α particles expelled per second from 1 gram of radium in radioactive equilibrium is four times the number at its minimum activity, and is equal to $2\cdot 5 \times 10^{11}$.

This number is in good agreement with the number 2×10^{11} , previously deduced from direct data, based on the heating effect of radium and the observed volume of the emanation*.

I think these experiments show conclusively that the α rays from radium do carry a positive charge. We have seen that

* Rutherford (*loc. cit.*).

the numbers obtained are in good agreement, although the magnitude of the current due to the electrons varied considerably in the different experiments. The fact that the current either in the positive or negative direction was independent over a wide range of the strength of the magnetic field, when once a certain small value of the magnetic field had been reached, shows that the strength of the field was sufficient to bend back all the slow-moving electrons emitted by the plates.

The failure of the earlier experiments to detect the charge carried by the α rays led to the suggestion that the α particle was uncharged at the moment of expulsion, but gained a positive charge in its passage through the gas. It is probable that the α particle, if initially uncharged, would lose a negative electron by collision with the gas molecules, and so retain a positive charge. This point came up in the discussion at the close of the Bakerian Lecture (*loc. cit.*) last year, and was referred to by me in the paper "Present Problems of Radioactivity," read before the International Congress of Arts and Sciences, St. Louis, 1904. The same suggestion was also made by Bragg*.

There does not, however, now seem any doubt that the α particle is charged at the moment of its expulsion. The pressure of the gas in the experiments was so low that only a small fraction of the α particles could come into collision with the gas molecules. This is brought out by the comparison of the values of the positive and negative currents in a strong magnetic field. The difference between the currents in the two directions is probably due to the small ionization produced in the residual gas by the passage of the α particles through it. In some cases the value of this ionization current was not more than one-tenth of the current due to the charge on the α particles alone. This indicates that only a small fraction of the α particles come into collision with gas molecules. On the other hand, the magnitude of the charge carried by the α rays was independent of the state of the vacuum over a considerable range, showing that the residual gas had no effect in altering the number of charged α particles absorbed in the upper plate.

We may thus conclude that the α particles are positively charged at the moment of their release from the radium plate, and, remembering that the film of radium used in the experiments was very thin, there is no obvious reason for supposing that they are not charged at the moment of their expulsion from the radium atoms.

* Phil. Mag. Dec. 1904.

Origin of the Slow-Speed Electrons.

We have seen that J. J. Thomson has shown that a number of slow-speed electrons are emitted with the α particles from a plate of radio-tellurium. The experiments described above show that this is equally the case with radium. The magnitude of the current due to these electrons is sufficient to completely mask the effect due to the charge carried by the α particles, and in some cases is twenty times as great. The question now arises, whether these electrons are projected from the radioactive matter itself, or are emitted from the plates on which the α particles impinge. The fact that the current without a magnetic field is greater when the lower plate is negative than when it is positive shows that a greater number of electrons are emitted from the lower plate. If the electrons were only emitted from the lower plate, the positive current should greatly exceed the negative. The results indicate that these electrons arise from both the upper and lower plate, but to a greater extent from the latter. This is borne out by the experiments when the radium film deposited on the glass plate is covered with thin aluminium-foil. The negative current is still the greater, but the difference is not nearly so marked. Since the electrons are probably not projected with sufficient velocity to pass through even one thickness of aluminium-foil, it seems probable that the electrons liberated from the radium itself and the glass plate would be absorbed in the aluminium-foil. The experiments as a whole indicate that the electrons escape both from the radium plate and from the surface in which they are absorbed. It seems probable that these electrons constitute a type of secondary radiation which results from the impact of the α particles on matter. Since half the α particles emitted from the radium are projected into the lower plate and the other half are projected upwards, it is to be expected that more would escape from the lower than from the upper plate. It is difficult to settle whether the radium itself emits any of these slow-speed electrons at the moment of expulsion of the α particle. There is no reason, however, to doubt that such electrons would be liberated by the bombardment of the radium by the α particles projected from its own mass.

The existence of this type of secondary radiation, set up when the α particles pass through matter, readily explains some results obtained by Mme. Curie in her experiments on the absorption of the α rays from polonium. The ionization current between two parallel plates was compared when two screens of different materials, placed over the

polonium, were interchanged. For example, with screens of aluminium and cardboard, the current was greater when the aluminium was uppermost. Similar results were obtained with other materials. These results indicate that different amounts of secondary radiations—probably in the form of the slow-speed electrons in question—were produced at the surface of the matter through which the rays passed.

Charge carried by the β Rays.

It is of importance to determine the total number of β particles emitted from one gram of radium in radioactive equilibrium, as, theoretically, it is to be expected that this number should bear a definite relation to the total number of α particles expelled. Now radium in radioactive equilibrium contains four substances, viz., radium itself, the emanation, radium A, and radium C, which emit α particles. On the other hand, β particles are only expelled from one product, radium C. These substances are successive products of radium, and, when equilibrium is reached, the same number of atoms of each break up per second. If the disintegration of the atom of each product is accompanied by the expulsion of one α particle and the case of radium C also of one β particle, the number of α particles emitted from radium in radioactive equilibrium will be four times the number of β particles. The number of β particles from radium in equilibrium will thus be equal to the number of α particles expelled at its minimum activity, when the emanation and its further products are absent.

Some experiments have been made by Wien* to determine the number of β particles expelled from a known quantity of radium. About 4 milligrams of radium bromide were enclosed in a platinum cylinder, which was insulated in a larger tube, and the air exhausted. The platinum cylinder was found to gain a positive charge, since the β particles, some of which were projected through the cylinder, carried with them a negative charge. The rate of escape of electricity from the platinum cylinder corresponded to 2.91×10^{-12} ampere. If each β particle carries the observed ionic charge of 1.13×10^{-19} , this corresponds to an escape of 2.66×10^7 β particles per second. From one gram of radium, the corresponding number would be 1.14×10^{10} .

It is known from experiments upon the absorption of the β rays from radium that some of the β particles are easily absorbed in passing through a small thickness of matter. The above estimate is for this reason far too small.

* Wien, *Physik. Zeit.* iv. p. 624 (1903).

In order to eliminate as far as possible the error due to absorption of the β rays in the radium itself and the envelope containing it, I employed a different method. Instead of using the radium compound itself, a body made active by exposure in the presence of the radium emanation was used as a source of β rays. A lead cylinder 4 cms. long and 4 mms. in diameter was made the negative electrode in a vessel containing a large quantity of radium emanation. After about three hours exposure, the excited activity reaches a maximum. The lead rod was then removed, and the intensity of the γ rays from it was compared directly by means of an electroscope with that due to a known weight of pure radium bromide in radioactive equilibrium. The γ rays, rather than the β rays, were chosen as a means of comparison, as the absorption of the γ rays in the lead rod or the radium envelope is very small. Suppose, for example, that the γ ray effect from the active deposit in the lead rod was equivalent to m milligrams of radium bromide. Now the β and γ rays from the radium or the active deposit on the rod arise only from the one product radium C. Since the β and γ rays always occur together and in the same proportion, the total number of β particles emitted by the lead rod is equivalent to the number emitted by m milligrams of radium bromide. Since the active deposit on the rod is extremely thin, half of the β rays projected from it escape without absorption. The stoppage of the β particles by the active matter itself, such as would occur if radium bromide were directly used, is thus avoided.

Immediately after testing, the lead cylinder was wrapped with a thickness of aluminium-foil just sufficient to completely absorb the α rays. It was found experimentally that the α rays were completely stopped by 13 layers of foil, each of thickness $\cdot 00031$ cms. 17 layers of foil, that is a thickness of aluminium of $\cdot 0053$ cm. were added in all. This ensured that the absorption of the β particles in the aluminium screen was a minimum, consistent with complete absorption of the α rays. The lead rod was made the central electrode A in the apparatus of fig. 2. The outer cylinder B was connected with one pole of a battery, the other pole of which was earthed, and the central electrode with a Dolezalek electrometer, using a suitable capacity in parallel. The air was exhausted as rapidly as possible, and measurements were begun usually about 20 minutes after the removal of the active rod from the emanation.

The potential of the external cylinder was alternately reversed, and the currents measured. As we have seen in the

experiments on the charge carried by the α rays, half the algebraic sum of the currents observed with reversal of the

Fig. 2.

potential represents the value ne , where n is the number of β particles escaping from the central electrode per second, and e the charge on each particle.

The value of ne was found to decrease with the time at the same rate as the rod lost its β activity, measured in the usual way by an electroscope. Knowing the curve representing the variation of the β ray activity with time, the value of ne at any time can be expressed in terms of the value of ne at the moment of removal of the rod from the emanation.

The following numbers illustrate the experimental method. At the moment of removal, the γ ray activity of the rod corresponded to 4.20 milligrams of radium bromide. The value of ne was determined after the rod had been removed 33 minutes. From comparison with the known curve, the β ray activity had during that time fallen to 74 per cent. of the initial value. The value of ne , reduced to the initial value, was found to be 1.05×10^{-11} ampere. Taking e as 1.13×10^{-19} coulomb, the value of n is thus 9.3×10^7 .

This is the number corresponding to 4.2 milligrams of radium bromide. Remembering that half of the β particles are projected into the lead which absorbs most of them, it can

readily be calculated that one gram of radium in radioactive equilibrium emits 7.6×10^{10} β particles per second.

A second series of experiments made under different conditions gave a value of 7.0×10^{10} .

Taking the mean of these two values, we may thus conclude that the *total number of β particles expelled from one gram of radium per second is 7.3×10^{10} .*

The total number of α particles expelled per second from one gram of radium at its minimum activity has been shown to be 6.2×10^{10} . The approximate agreement between these numbers is a strong indication of the correctness of the theoretical views, previously discussed. It is to be expected that the number of β particles, deduced in this way, should be somewhat greater than the number of α particles, for the β particles give rise to a secondary radiation, consisting also of negatively charged particles moving at a high speed. These secondary β particles, arising from the impact of the β particles on the lead, will pass through the aluminium screen, and add their effect to those directly shot out. For this reason, probably, the experimental number is somewhat too large. The results, however, indicate that four α particles are expelled from radium in radioactive equilibrium for each β particle, and thus confirm the theory of successive changes.

Deductions from the Results.

The determination of the total number of α particles expelled per second from one gram of radium is of great value, for by its means we are enabled to directly deduce the magnitude of other important physical constants in radioactivity. The methods of calculation of some of these quantities will now be briefly given.

Life of Radium.—We have seen that one gram of radium at its minimum activity expels 6.2×10^{10} α particles per second. It seems probable that only one α particle is expelled during the disintegration of the radium atom, so that 6.2×10^{10} atoms of radium break up per second per gram. The number per gram per year is 1.95×10^{16} . It has been experimentally deduced that one cubic centimetre of hydrogen at standard pressure and temperature contains 3.6×10^{19} molecules. Taking the atomic weight of radium as 225, it follows that one gram of radium contains 3.6×10^{21} atoms of radium. The fraction λ of the radium atoms which break up per year is thus

$$\frac{1.95 \times 10^{16}}{3.6 \times 10^{21}} \quad \text{or} \quad 5.4 \times 10^{-4}.$$

Thus in a gram of radium about half a milligram disintegrates per year. Now it is probable that, as in every other radioactive product, the number of atoms of radium which break up is always proportional to the number present. Thus if n is the number present after an interval t , and n_0 the initial number, then $\frac{n}{n_0} = e^{-\lambda t}$. The value of λ is 5.4×10 (year) $^{-1}$,

so that the time required for the radium to be half transformed is about 1280 years. The average life of radium is thus 1850 years.

Volume of the Emanation.—Each atom of radium in breaking up is supposed to produce one atom of emanation. If q_0 is the number of atoms of emanation produced per second per gram, the total number of atoms N_0 present when radio-

active equilibrium is reached is given by $N_0 = \frac{q_0}{\lambda}$, where λ is the radioactive constant of the emanation. Now $q_0 = 6.2 \times 10^{10}$, and $1/\lambda = 480000$, thus $N_0 \approx 3.0 \times 10^{16}$.

But one cubic centimetre of any gas contains 3.6×10^{19} molecules. Thus the maximum volume of the emanation to be obtained from one gram of radium in radioactive equilibrium is equal to $\frac{3.0 \times 10^{16}}{3.6 \times 10^{19}}$ c.c. = 0.83 cubic millimetres.

Now Ramsay and Soddy found experimentally that the volume of emanation to be obtained from one gram of radium was about one cubic millimetre. The numbers are thus in good agreement.

Heating Effect of Radium.—Rutherford and Barnes have shown that the heating effect of radium and of its various products is due to the bombardment of the α particles expelled from them. From measurements of the constants of the α particle, I deduced that its kinetic energy was about 5.9×10^{-6} erg.

Radium in radioactive equilibrium emits 2.5×10^{11} α particles per second per gram. The emission of energy in the form of kinetic energy of the α particles thus corresponds to 126 gram-calories per gram per hour. This number is in fairly good agreement with the value 100, first determined experimentally by Curie and Laborde.

If the heating effect of radium is assumed to be a measure of the kinetic energy of the α particles, we may conversely deduce that the average energy of the α particle emitted from radium and its products is 4.7×10^{-6} erg.

Number of Ions produced by an α particle.—Knowing the number of α particles expelled per second from a thin film

of radium, and the saturation current produced when the radiation is all absorbed in the gas, we can at once deduce the number of ions produced in air at atmospheric pressure and temperature by the passage of a single α particle through it.

A weight of .484 milligram of radium bromide spread in the form of a thin film on an aluminium plate emitted 8.7×10^6 α particles into the gas per second. The saturation current observed between parallel plates at sufficient distance apart to absorb most of the rays was 8.4×10^{-8} ampere. Taking the charge on an ion as 1.13×10^{-19} coulomb, this current corresponds to a production of 7.5×10^{11} ions per second in the gas. But this number was produced by 8.7×10^6 α particles. The average number of ions produced by each α particle, expelled from radium itself, is thus 86000. Now Bragg has shown that an α particle passing through air produces nearly the same number of ions per unit length of its path, and the ionization ceases fairly abruptly. The range in air for the α particles from radium at its minimum activity is about 3.0 cms. The number of ions produced per cm. of path in air at normal pressure and temperature is thus 29000. The number per cm. of path at a pressure of one millimetre of mercury would be 38.

Townsend found that the maximum number of ions produced by an electron per cm. of path at a pressure of one mm. of mercury was 21. At this maximum it was deduced that each collision of the electron with the molecules in its path resulted in the production of ions. Since the α particle produces 38 ions under the same conditions, we may conclude that an α particle is nearly twice as efficient an ionizer as the electron at its maximum efficiency. Such a result indicates that the α particle has a somewhat larger sphere of action than the electron, and is able to ionize about two molecules for the electron's one. This is not unexpected, since the α particle is of atomic dimension, while that of the electron is small compared with an atom.

Energy required to produce an Ion.—A deduction of the average energy required to produce an ion by collision of the α particle with the gas molecules can be made, if the range of velocity, over which the α particles ionize the gas, is determined. I have shown in my paper* “Some Properties of the α Rays from Radium,” that the α rays, emitted by a thin film of radium at its minimum activity, are initially projected with a velocity .88 v_0 , where v_0 is the initial velocity of projection of the α particles from radium C. The α particles cease to ionize the gas when the velocity falls

* Phil. Mag. July 1905.

208 Dr. Fleming: *Ratio between Mean Spherical and*

to $\cdot 64 v_0$. From this it can at once be deduced that $\cdot 48$ of the total energy of the α particle, shot out by radium itself, is absorbed when it ceases to ionize the gas. Now it can be calculated from the heating effect of radium at its minimum activity—25 gram-calories per hour per gram—that the kinetic energy of the α particle is $4\cdot 7 \times 10^{-6}$ erg. The amount of energy absorbed when the α particles just cease to ionize the gas is $2\cdot 3 \times 10^{-6}$ erg. Assuming that this energy is used up in ionization, and remembering that the α particle from radium itself produces 86,000 ions, the average energy required to produce an ion is $2\cdot 7 \times 10^{-11}$ erg. This is equivalent to the energy acquired by an ion moving freely between two points differing in potential by 24 volts.

McGill University, Montreal,
May 1, 1905.

XXVI. *On the Ratio between the Mean Spherical and the Mean Horizontal Candle-Power of Incandescent Electric Lamps.*
By J. A. FLEMING, M.A., D.Sc., F.R.S., Professor of
Electrical Engineering in University College, London*.

A PAPER was read before the Physical Society on November 11th, 1904†, by Mr. G. B. Dyke, B.Sc., in which, amongst other matters, he gave the results of numerous measurements made in the Pender Electrical Laboratory of University College, London, of the ratio of the mean spherical candle-power of incandescent electric lamps to the mean horizontal candle-power, taken when the lamp was rotating round a vertical axis. In all cases the ratio of the mean spherical to mean horizontal candle-power was experimentally found to be a number near to 0·78 for about nine different types of electric glow-lamps. This constant ratio must depend upon definite optical facts, and cannot be a matter of accident. That this is the case can be shown by considering a typical instance.

Let us suppose a short straight filament ab (fig. 1) rendered incandescent to be placed vertically in the centre of a sphere described by the revolution of a semicircle PHQ round a diameter PQ , coinciding with the direction of the filament. Let the length of the filament be small compared with the radius $FH=r$ of the sphere. Let I_H represent the

* Communicated by the Physical Society: read June 16, 1905.

† See Mr. G. B. Dyke, "On the Practical Determination of the Mean Spherical Candle-Power of Incandescent and Arc Lamps," *Phil. Mag.* ser. 6, vol. ix. p. 136, Jan. 1905; also *Proc. Phys. Soc.* vol. xix. p. 399 (1905).