

THE IONIZATION AND STOPPING POWER OF VARIOUS  
GASES FOR ALPHA-PARTICLES FROM POLONIUM: I

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ABSTRACT

Determinations of the differential ionizations and stopping powers of hydrogen, neon, nitrogen, oxygen, argon, and methyl iodide have been made at intervals along the range of  $\alpha$ -particles from polonium. From the results of these and other determinations it is shown that the energy lost by the  $\alpha$ -particle per ion is nearly independent of the speed throughout the range. There are slight but definite systematic deviations from constancy for oxygen and methyl iodide.

I. INTRODUCTION

THE energy lost by an  $\alpha$ -particle in air per pair of ions formed has been shown by Kapitza,<sup>1</sup> by I. Curie,<sup>2</sup> and by Gurney<sup>3</sup> to be nearly independent of the speed, or range, of the  $\alpha$ -particle. In other words, the quantity  $(\partial E/\partial I)_0$  is constant along the range, where  $E$  is the energy of the  $\alpha$ -particle, and  $I$  is a quantity proportional to the number of ions produced.<sup>4</sup> If this were true for all gases the quantity  $\sigma(\partial I/\partial x)_0/(\partial I/\partial x)$  should be independent of the ranges in all cases, where  $x$  is the distance travelled by the  $\alpha$ -particle, and  $\sigma$  is the differential stopping power, that is  $\sigma = (\partial E/\partial x)/(\partial E/\partial x)_0$ . For we have.

$$(\partial E/\partial x) = (\partial E/\partial x)/(\partial I/\partial x) = \sigma(\partial I/\partial x)_0/(\partial I/\partial x). \quad (1)$$

We have tested this relationship for a number of gases. Instead of  $(\partial I/\partial x)_0$ , however, we have taken an average  $\partial I/\partial x$  for the gases  $N_2$ , A, He,  $NO^*$ ,  $N_2O^*$  all of which have ionization curves whose ordinates are closely proportional throughout the range, and stopping powers which are nearly constant.<sup>5</sup> At each point of the range the arithmetic mean of the values of  $\log \partial I/\partial x$  for the various gases is the logarithm of the average  $\partial I/\partial x$  which we will call  $(\partial I/\partial x)_1$ . In other words,  $(\partial I/\partial x)_1$  is the geometric mean of the values of  $\partial I/\partial x$ . In this way a more representative curve is obtained from which chance deviations, which might occur in the curve of a single gas, may be expected to be largely eliminated. The values of the ratio  $\rho_2 = \sigma(\partial I/\partial x)_1/(\partial I/\partial x)$  for various gases and residual ranges are compared in Table I with those of  $\rho_1 = (\partial I/\partial x)_1/(\partial I/\partial x)$ .

<sup>1</sup> Kapitza, Proc. Roy. Soc. (London), **A102**, 48 (1922).

<sup>2</sup> I. Curie, Ann. d. physique (10) **3**, 299 (1925).

<sup>3</sup> Gurney, Proc. Roy. Soc. (London), **A107**, 332 (1925).

<sup>4</sup> The subscript zero will always be taken to denote that air is the gas to which the symbol so designated refers.

<sup>5</sup> The data for the gases with an asterisk were taken from the paper by Gibson and Eyring which follows this.

TABLE I

Values of the ratios  $\rho_2 = \sigma(\partial I/\partial x)_1/(\partial I/\partial x)$  and  $\rho_1 = (\partial I/\partial x)_1/(\partial I/\partial x)$  for various gases and residual ranges.

Residual range (cm)		0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2	1.4	1.6	$\Delta$
H <sub>2</sub>	$\rho_1$	419	419	451	472	514	535	569	573	589	606	615	621	12.5
	$\rho_2$	131	135	137	136	136	132	132	131	133	136	136	137	1.5
He†	$\rho_1$	158	157	155	157	159	159	159	158	157	156	154	153	1.0
	$\rho_2$	111	115	116	115	113	110	111	112	113	113	114	115	1.3
Ne	$\rho_1$	212	222	223	211	197	192	188	185	183	180	177	174	8.3
N <sub>2</sub> †	$\rho_1$	134	134	138	139	140	140	140	139	140	139	138	138	1.1
	$\rho_2$	135	134	137	138	141	141	138	137	138	137	136	137	1.0
O <sub>2</sub>	$\rho_1$	126	128	127	127	121	119	118	117	116	116	115	114	3.6
	$\rho_2$	124	129	130	129	127	125	124	123	123	122	121	117	2.2
NO*†	$\rho_1$	115	116	120	119	119	117	118	119	119	120	120	120	1.0
N <sub>2</sub> O*†	$\rho_1$	110	105	104	104	103	102	102	101	102	101	101	103	1.6
A	$\rho_1$	108	107	108	110	111	112	112	112	112	112	112	110	1.4
	$\rho_2$	99	100	100	103	103	104	104	104	104	104	104	103	1.3
CH <sub>3</sub> I	$\rho_1$	270	270	259	255	255	254	255	258	262	270	274	277	2.8
Air*†	$\rho_1$	115	120	120	118	118	117	118	118	118	118	117	117	0.7

\* Data taken from Gibson and Eyring.

† These gases were used for obtaining the average  $(\partial I/\partial x)_1$ .

In the last column  $\Delta$  signifies the average deviation from the mean in percent. The gases which show an undoubted deviation from constancy of  $\rho_1$  are hydrogen, neon, oxygen and methyl iodide. It is a curious coincidence that air which has been chosen as a standard of comparison in this should show the least deviation from the average. In every case  $\Delta$  for  $\rho_2$  is less than for  $\rho_1$ . In hydrogen the improvement is very marked. Neon, which shows the second largest deviation for  $\rho_1$  would also have a very much smaller deviation for  $\rho_2$ , since the average stopping powers for this gas found by Gurney<sup>3</sup> show a trend of about the right amount to counterbalance the trend in  $\rho_1$ . Differential stopping powers have not yet been obtained for neon. Oxygen and methyl iodide, however, show trends which seem to be definitely beyond the limit of experimental error. We have checked data for both gases repeatedly and always with the same result. We may conclude therefore that the constancy of  $\partial E/\partial I$  along the range is not quite perfect, although the closeness with which this approximate rule is obeyed is very significant. The stopping powers of CH<sub>3</sub>I have been determined, but are subject to errors which we will discuss later. For this reason  $\rho_2$  was not calculated for this gas. The data are sufficiently accurate to indicate that there would be a slight improvement here also, but not sufficient to remove the trend in  $\rho_2$ . In the attempts which so far have been made at a theoretical interpretation of ionization and stopping power the constancy of  $\partial E/\partial I$  does not appear to

have been recognized as a condition which a complete theory should satisfy. Nor is it derivable without further assumptions from the theories so far proposed. It is not surprising that this point should have been overlooked hitherto in view of the lack of accurate energy determinations before the work of Kapitza, and the fact that large deviations from proportionality of the  $\partial I/\partial x$  curves, as in hydrogen, were known to exist. The ionization and stopping power data hitherto available were inadequate to show the correlation between these deviations from proportionality and the variation in stopping power along the range which is apparent in the data of Table I. A constant energy loss per ion would be explained if only a single type of ionization were concerned, but this cannot be so, in view of the variation in stopping power with atomic number which shows that the internal electrons must play some part in the energy loss produced by heavy atoms, while the ionization in hydrogen and helium proves that loosely bound electrons also are readily affected by the  $\alpha$ -particle. Transference probably contributes only a small amount to the energy loss, in view of the experiments of Sponer,<sup>6</sup> Dymond,<sup>7</sup> and Glockler,<sup>8</sup> which show that the efficiency of excitation for transference is much smaller than for ionization. The kind of electron excitation, however, which subsequently results in dissociation of the molecule into atoms is likely to play an important part in the lighter molecules.<sup>3</sup> There seems to be a parallelism between the efficiency of an excitation by collision and the width of the corresponding line or band in the spectrum of the gas. If we may use this as an argument, the excitation resulting in dissociation should be highly efficient in view of the width of the absorption band following the band convergences which in the theory of Franck<sup>9</sup> involve this process also. There are thus a large number of processes involved producing very diverse losses of energy in the moving particle. We must also take into consideration the fact that secondary ionization by the ejected electrons is responsible for the major portion of the ionization in the early part of the range, but contributes a smaller fraction when the velocity of the  $\alpha$ -particle is relatively small, as at the maximum of the ionization curve, and beyond. That the resultant loss of energy per ion from all these sources is so nearly independent of velocity seems to show that their relative frequencies are nearly the same at different parts of the range. It would seem also that these relative efficiencies in a given gas must be the same whether the ionizing particle is an electron or an  $\alpha$ -particle, as otherwise the change in the amount of secondary ionization along the range would necessarily produce a change in  $\partial E/\partial I$ . Further, since the proportion of singly charged  $\alpha$ -particles is already considerable at the maximum of ionization where the primary ionization is large, the relative efficiencies of these processes for singly and doubly charged helium ions cannot differ by any large amount.

<sup>6</sup> Sponer, *Zeits. f. Physik* **7**, 185 (1921).

<sup>7</sup> Dymond, *Proc. Roy. Soc.* **A107**, 291 (1925).

<sup>8</sup> Glockler, *The Efficiency of Electron Impact Leading to Resonance in Helium* (not yet published).

<sup>9</sup> Franck, *Zeits. f. Phys. Chem.* **120**, 144 (1926); *Trans. Faraday Soc.* **21**, Part 3 (1925).

When the energy of a secondary electron diminishes to the value below which it cannot produce a given excitation, the relative efficiency with which it produces this excitation must change very rapidly to zero. At first sight this appears to be incompatible with the constancy of  $\partial E/\partial I$ , and must in fact be responsible for at least part of the observed deviations, although these are only slightly in excess of experimental error. A possible explanation would be that a secondary electron produces the major portion of its excitations (and ionizations) while its energy is still in excess of the amount necessary to ionize the most firmly bound of the electrons which are affected to any large extent by the  $\alpha$ -particles. Then the identity of the relative efficiencies of the various processes for the three kinds of particles, electron,  $\text{He}^+$  and  $\text{He}^{++}$ , need only be assumed for speeds in excess of those necessary to produce the major portion of the excitations which actually occur. Since the energy of the secondary electrons is comparatively small on the average, this leads us again to the conclusion that only a small fraction of the electrons ejected can come from the deeper levels. It is possible that collisions of the second kind, involving ions which lack an electron from one of the deeper levels, may result in a number of excitations and ionizations of lower energy, but if so it seems necessary to assume the same relative frequency of production of the various types of excited atoms or ions by this process, as by collision with the moving particles.

## II. APPARATUS

The apparatus used in the determination of ionizations and stopping powers is essentially the same as that which Geiger<sup>10</sup> used in the accurate determination of ranges. It was found convenient, however, to make the whole apparatus of brass instead of glass, and to charge the gold leaf electroscope by a magnetic device. In Fig. 1 the essential parts of the apparatus are shown.

The upper chamber *A*, hereinafter called the ionization chamber, consists of a brass cylinder, 12 cm in diameter and 10 cm high. At the bottom it is fastened to a brass plate *C* 1 cm in thickness and 14 cm in diameter. Through the central part of this plate are drilled about 500 holes of 3 mm diameter over an area 8 cm in diameter. To the under side of the brass plate is fastened a thin sheet of mica *D* by means of cement and held in position by a brass plate *E* of 5 mm thickness and having the same number of holes as the upper plate. The purpose of the holes is to obtain a nearly parallel beam of  $\alpha$ -particles and to support the mica sheet with the minimum amount of bending under pressure, while giving a large area through which the  $\alpha$ -particles can pass. The mica sheet separates the upper and lower chambers and can withstand a difference in pressure of more than one-half atmosphere. It has a stopping power for  $\alpha$ -particles equivalent to about 2 cm of air at atmospheric pressure and 0°C. The lower chamber *B* has the same dimensions

<sup>10</sup> Geiger, *Zeits. f. Physik* **8**, 45 (1921).

as the upper one and will be designated as the retarding chamber. It contains a silver plate *F*, 6 cm in diameter, supported at a distance of 8 cm from the mica sheet. On the silver plate is deposited the source of  $\alpha$ -particles, polonium.

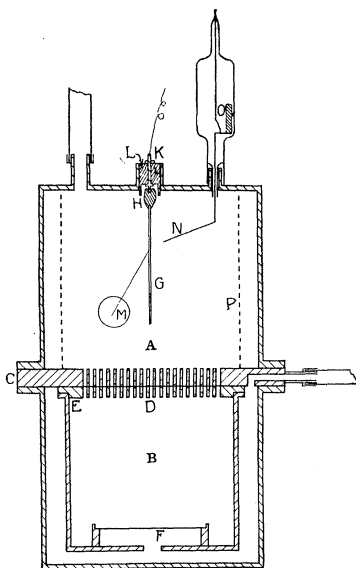


Fig. 1. Diagram of the ionization apparatus.

### III. PREPARATION OF GASES

Hydrogen was obtained by the electrolysis of NaOH solution and purified from oxygen and water by passing over heated platinized asbestos and through a liquid air trap. Helium was purified by passing through heated copper oxide to remove hydrogen and oxygen, and through a liquid air trap containing charcoal to remove water vapor and nitrogen. Oxygen was prepared by heating HgO in a tube which previously had been evacuated. Air for the ionization and retarding chambers was dried over fused KOH and  $P_2O_5$  before introduction into the apparatus. Argon containing from 1 to 2 percent of impurities, probably hydrogen and nitrogen, was dried and used without further purification. Neon was obtained "pure" from the Linde Air Products Co. of Buffalo, and further purified by passing through a liquid air trap. Methyl iodide was washed with dilute NaOH to remove iodine and hydroiodic acid and then dried with fused  $CaCl_2$ . The bromoform contained at first about 5 percent of ethyl alcohol, which was removed by repeated recrystallization in vacuo.

### IV. PREPARATION OF THE POLONIUM SOURCE

Decayed emanation tubes containing an equilibrium mixture of RaD, RaE and RaF were ground up and heated to a temperature sufficient to drive off the mercury and wax which were present. The glass was then dissolved

in hydrofluoric acid and the solution was diluted. Into this solution of polonium a silver plate was placed for 4 or 5 hours and received a large deposit of polonium quite evenly distributed. This is a very convenient way to obtain a uniform polonium source.

#### V. PROCEDURE

For a pressure of 2 cm in hydrogen and a chamber 11 cm long the air equivalent at atmospheric pressure is about 0.7 to 0.8 mm, and the speed of the  $\alpha$ -particles is therefore nearly constant in the ionization chamber. For hydrogen and helium a pressure of 2 cm was used, for neon a pressure of 8 mm, for nitrogen, argon and oxygen a pressure of 4 mm, for methyl iodide 2.5 mm and for bromoform 0.8 mm.

The speed of the  $\alpha$ -particles entering the ionization chamber was determined by the pressure of the air in the retarding chamber, and could be varied by increasing or decreasing the pressure of the air. From the dimensions of the apparatus the air equivalent at atmospheric pressure of the air in the retarding chamber could be obtained.

The pressure in the ionization chamber was measured by a McLeod gauge or mercury manometer, and the pressure in the retarding chamber by a large bore mercury manometer. The manometer was regulated to an accuracy of 0.3 mm, corresponding to a variation in the path of the  $\alpha$ -particle of about 0.003 cm.

After the pressure in the two chambers had been measured, the electro-scope was charged to about  $-200$  volts. A guard ring above the amber was charged constantly to  $-210$  volts to reduce the leak. During a run the potential of the gold leaf fell from  $-200$  volts to  $-30$  or  $-40$  volts. A constant rate of fall was proof that the saturation current was being obtained without ionization by collision. At 2 cm pressure in helium ionization by collision was appreciable at voltages around  $-200$  volts. In runs on helium at 2 cm pressure the voltage was kept below  $-180$  volts and it was found that constant rates of fall were obtained when the voltage on the gold leaf changed during a run to  $-30$  volts. We were thus sure that ionization by collision was not occurring in the ionization chamber. In hydrogen and air there was no ionization by collision for potentials of  $-200$  volts on the leaf from pressures of 1 mm to 20 cm and the ionization was also proportional to the pressure within that range. In helium the ionization was proportional to the pressure up to 20 cm, but at the lower pressures from 0.5 mm to 15 mm it was necessary to use low voltages. The range of the potential on the electro-scope was, however, great enough in all cases to prove that ionization by collision was absent during any of the runs made.

Keeping the pressure in the ionization chamber the same, the pressure in the retarding chamber was varied from zero to 20 cm, at which pressure all the  $\alpha$ -particles were stopped by the air and mica, so that none entered the ionization chamber. In this way the ionization curve for the last two cm of the path was obtained. The natural fall of the gold leaf was different for each gas, and amounted to 0.1 and 0.2 percent of the greatest rate of

fall of the leaf when the  $\alpha$ -particles were ionizing in the chamber. The ionization values were corrected for the decay of the source and for the natural fall of the electroscope.

The experimental values of the ionization are average values for the length of the ionization chamber. The true differential values were obtained

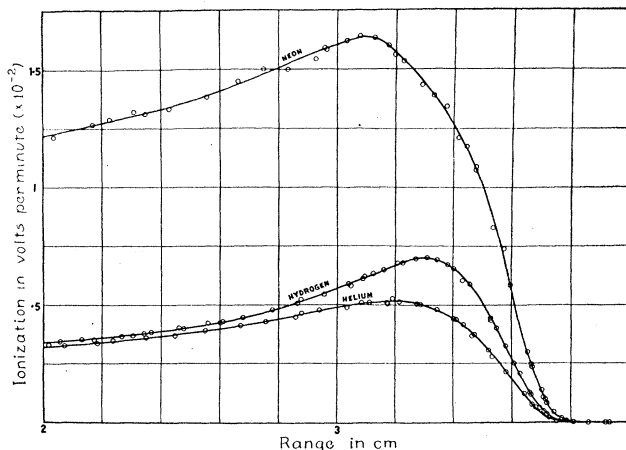


Fig. 2. Ionization curves of helium, hydrogen and neon at 2 cm pressure.

from them by a graphical correction and the figures are calculated for a pressure of 2 cm in each gas. The curves for hydrogen, helium and neon are shown in Fig. 2; those for nitrogen, argon and oxygen appear in Fig. 3, and those for methyl iodide and bromoform in Fig. 4. The ordinates in Fig. 3

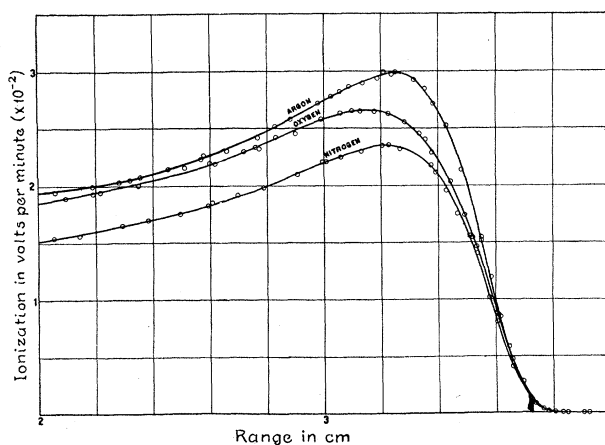


Fig. 3. Ionization curves of nitrogen, oxygen and argon at 2 cm pressure.

are drawn on a scale double those of Fig. 2, while the ordinates in Fig. 4 are four times those of Fig. 2. The ionization at the extreme end of the range was determined at short intervals, and the results are shown in Fig. 5. In Figs. 2, 3 and 4 the experimental points have been drawn in to show the

degree of accuracy obtained. Only a few of the experimental points at the end of the range were included in these graphs, as the scale is too small to show all of them clearly. In Fig. 5 experimental points are shown only for neon and hydrogen.

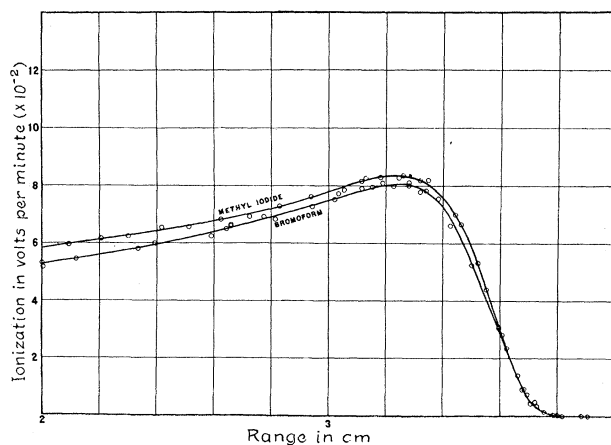


Fig. 4. Ionization curves of methyl iodide and bromoform at 2 cm pressure.

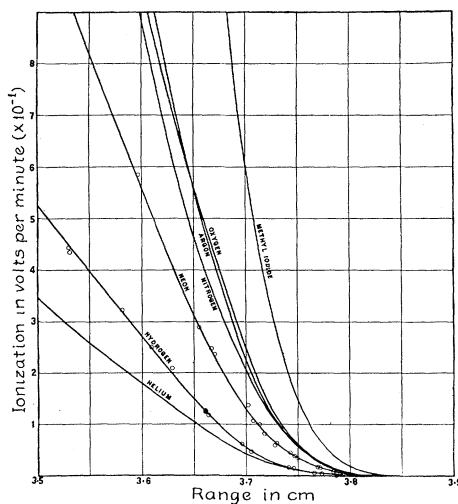


Fig. 5. End of the ionization curves of all the gases studied.

## VI. STOPPING POWER

The method, in principle, is identical with that of Gurney.<sup>3</sup> The stopping power of a gas is the ratio of the distances in air and in the gas under consideration which an  $\alpha$ -particle will go for a decrease in speed of the same amount in the two gases. Using an ionization chamber of fixed dimensions, the stopping power of hydrogen is the ratio of the pressures required just to prevent the  $\alpha$ -particles from reaching the top of the chamber in hydrogen



to the pressure required to do the same in air. The pressure of air in the retarding chamber was fixed so that the  $\alpha$ -particles emerging from the mica sheet would have a definite residual range, say 3.5 mm. The stopping power measured was then an average value for the last 3.5 mm of the range. Ionization pressure curves were measured for air and hydrogen, and the ratio of the pressures at which ionization became constant in the two gases was taken as the stopping power of the hydrogen. Since it was hard to determine accurately the exact pressure at which the ionization became constant, the curves obtained for hydrogen and air were reduced to the same total ionization value. The ratios of the abscissas at a number of corresponding ordinates near the highest value of ionization were obtained and their average was taken as the stopping power. It was noticed that the ionization for air and hydrogen did not remain constant, but reached a maximum as the pressure was increased.<sup>11</sup>

One determination only was made on the stopping power of a gas for higher speed  $\alpha$ -particles, namely for methyl iodide at the beginning of the range of polonium, using again the method of Gurney. The stopping power of methyl iodide was found to be 2.6 and is an average value for the  $\alpha$ -particles of polonium up to a range of 1.6 cm measured in air.

The results of these determinations are given in Table II, along with a few of Gurney's results.

TABLE II  
*Stopping powers*

Residual Range	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	He	A	CH <sub>3</sub> I
0.6 mm	0.235	1.018	0.906	0.151	0.925	2.10
1.6 mm	0.282	1.018	0.929	0.165	0.913	2.29
2.6 mm	0.283	1.047	0.945	0.169	0.89	2.44
3.6 mm	0.293	1.018	1.001	0.172	0.935	2.61
3.5 mm (G)	0.309		0.981	0.179	0.914	
1.4 cm (G)	0.247				0.920	
3.8 to 3.5 cm (G)	0.214		1.05	0.175	0.930	2.6 (3.8 to 2.2 cm)

Gurney's values are indicated by (G), all the values in the last three horizontal rows being taken from his paper, with the exception of the last value for methyl iodide. It is evident that there is a maximum stopping power for hydrogen. In the last centimeter of the range the ionization reaches a maximum, and falls off rapidly to zero. Whether the stopping power has a maximum or a minimum depends on the choice of air as standard.

<sup>11</sup> After emerging from the mica sheet, there is a portion of the path before the  $\alpha$  particles emerge from the holes in the upper brass plate, in which the ions produced are partially shielded from the field. By a somewhat involved calculation, which we shall not give here, we were able to reproduce the form of the experimental curves and the position of the maximum, assuming that all ions up to a certain distance (0.8 cm in the case of hydrogen) failed to be collected. The calculation showed that the effect of this on the stopping power as calculated from the uncorrected experimental curves was small for the lighter gases but considerable for methyl iodide. This point is discussed further in the following paper by Gibson and Eyring.

The experimental values of the stopping power are averages over a certain part of the range. We may calculate the differential stopping power for each speed of the  $\alpha$ -particle from these average values as follows:

The distance which an  $\alpha$ -particle of residual range  $R$  will travel is  $\int_0^R (1/\sigma) dR$ , where  $\sigma$  is the differential stopping power. The average stopping power obtained experimentally is given by the equation

$$\int_0^R (1/\sigma) dR = R/\sigma_{\text{exp}}$$

or

$$\frac{1}{\sigma} = \frac{\partial}{\partial R} \left( \frac{R}{\sigma_{\text{exp}}} \right).$$

Plotting  $R/\sigma_{\text{exp}}$  against  $R$  we may obtain  $1/\sigma$  graphically by drawing tangents to the curve. This was done for hydrogen, helium, argon, oxygen, and the results are shown on Fig. 6. The ionization curves in Figs. 2, 3, 4 and 5,

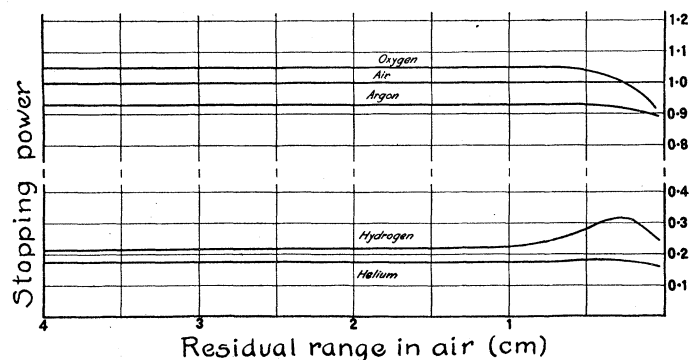


Fig. 6. Stopping power of various gases as a function of the residual range in air.

together with the differential stopping powers in Fig. 6, were used in the preparation of Table I.

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