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Interception and Scattering of Electrons and Ions

By KARL K. DARROW

This article deals with a couple of aspects of one of the amplest questions of modern experimental physics: the question of what happens when an electron (more generally, an electron or a proton or a charged atom of any kind) collides with an atom or a molecule. It is well known, of course, that if the electron has energy enough, it may excite or ionize the atom. There are many different modes of excitation, and often several of ionization; the variety of possibilities is wide. If any of them occurs at an encounter, the electron loses energy and speed, and may suffer a change in the direction of its motion—a "scattering," as this is called. Even if it loses no measurable amount of energy at a collision, it may be "scattered," that is to say, deflected. The scattering and the energy-losses of the electrons are studied both on their own account, and because of the light they shed on what is happening to the atoms.[1]

IMAGINE a stream of electrons projected, all with known and uniform velocity and along the same direction, into a rarefied gas. Perhaps it ionizes the gas; if so, positive ions appear, and one may detect them and identify them and count them in any of various ways, without concerning oneself about the destiny of the ionizing electrons. Or perhaps it excites the gas without producing ions; if so, the atoms (or molecules) send forth light, and one may detect the excitation and identify the manner and measure the likelihood thereof, without paying any attention to the corpuscles responsible. Nevertheless, these corpuscles also must have been affected; they must have given up some at least of their kinetic energy, and if they still retain some motion, it is probably no longer in the same direction as at first.

If there is ionization or excitation of the gas, there should be electrons wandering off obliquely from the stream, and moving more slowly than when they entered the gas; in technical language, there should occur "scattering with loss of energy." Even if the incoming corpuscles are moving too slowly to ionize or excite, there might be—and there are—electrons wandering off obliquely with practically undiminished speed; they have suffered "elastic impacts" with atoms or molecules, they have been deflected merely, or "scattered without loss of energy." And even if the incoming corpuscles are moving fast enough to ionize or excite, some may be scattered with undiminished speed while others are spending some of their energy in these operations. Also, some of

[1] This article, in somewhat altered form, is to appear as a chapter in a forthcoming book on ionization and conduction in gases.

the electrons may adhere to atoms or molecules.[2] One sees that there are several items of knowledge about the effects of the gas upon the electron-stream, which cannot be discovered by studying the inverse effects of the electron-stream upon the gas, the formation of ions or of excited atoms; it is necessary to observe the stream itself. Even our knowledge of the latter effects may be improved by examining the former. These are the purposes of the experiments which I shall now describe.

The first (and the most) of these experiments may seem rather paradoxical, in view of what I have just been saying; for they are experiments not on electrons of the stream, but on the *absence* of electrons from the stream. One sends a beam of these corpuscles (or, it may be, a beam of protons or of once-ionized potassium atoms) across a stratum of gas, measures the number which go in and the number in the emerging beam, and puts down the value of the difference as the number which "vanish from the beam." "Vanish" is a good word in this connection; it is not meant, of course, that the missing corpuscles and their charges literally cease to be; it is meant simply that they do not belong among those which go straight through with undiminished speed and undeflected path, as though the gas were not there. I will say that they have been "intercepted," for this is a word which does not imply any choice among the varied possibilities of stoppage, adhesion, and deflection with or without loss of energy. Experiments on interception of fast electrons—up to 30,000 equivalent volts—were first performed at the beginning of this century; but the earliest accurate work on slow electrons—say 50 equivalent volts and downward—is only ten years old.

The results of these experiments are very striking; but of course they yield only a small part of what is wanted. We want to know what becomes of the "vanished" electrons, which way they have gone and with what residual speed—the total number and the distribution-in-direction of those which have been scattered without loss of energy; the total number and the distribution-in-energy and the distribution-in-direction of those which have ionized or excited the atoms which they struck; and the number of those which have stuck to atoms, if such there be.

Such information, as anyone would foresee, is harder to acquire. Of the distribution-in-direction of the scattered electrons, nothing was known four years ago; and what in this last quadrennium has been ex-

[2] Some gases being monatomic and others not, it is necessary to say "atoms or molecules" when making general statements, if one wishes to be exact; but in the following pages I shall often use either word by itself, even when the statement in which the term occurs is meant to apply to gases of both kinds.

plored is very little, compared with what remains. As for the distribution-in-energy, the first step in determining it was taken some sixteen years ago. It was indeed a great step; for it led to the discovery of the process of excitation, the transfer of energy from moving electrons to atoms which shift these latter from their normal condition into one or another of their "excited" states.[3] But it was only a beginning; the method had to be much modified and refined, to make it capable of finding the answers to such questions as I have phrased above; and the modifications were scarcely even imagined as lately as four years ago. Hence the reader must not expect to be introduced to a very great body of systematized knowledge. As for experiments on protons and on other kinds of charged atoms, they too are all extremely recent.

I begin with the experiments on interception of electrons.

Suppose then that a beam of electrons is sent across a tube, having first been limited by a sequence of slits or holes so that it has a definite contour, like the beam of a searchlight, which it retains all the way across the tube if there is vacuum. Further, suppose that on the far side of the tube there is a collector just large enough to swallow up the entire beam so long as it does not spread, but no larger; or alternatively, a collector covered by a screen pierced with a hole just large enough to let the beam, or a fraction of it, pass through. Even so, the result may depend on the diameter of the beam in a way which the reader will see for himself later on; it is best to think of a very narrow pencil of corpuscles.[4]

When a gas is introduced into the tube, the current into the collector will decrease. The decrease will be proportional to the density of the gas, so long as this is not too great; and it will be possible to define a "cross-section of the molecule for interception of electrons" in the same general way as is the custom in many other fields. Which is to say: denote by dx the distance which the beam traverses through the gas; by Q the number of electrons which enter the gas per unit time, hence by Qe the amount of charge which in unit time would arrive at the collector were the gas away; by Re the amount which in unit time does actually arrive at the collector; by N the number of molecules per unit volume: then the cross-section in question—call it σ—will be defined

[3] That is to say, the discovery by experiment; it had been predicted by Bohr (for the history of these matters, see for instance my "Introduction to Contemporary Physics," Chapter VIII).

[4] Of course this is an ideal which can never be perfectly realized. No matter how many diaphragms may be set up in a row to narrow and sharpen the beam, there will always be transverse motions of the electrons, relatively more important the smaller the forward velocity is made. Moreover the mutual repulsion of the corpuscles will tend to widen out the beam by driving its members apart. This is one of the reasons why experiments in this field were first performed on fast electrons, then extended to smaller and ever smaller velocities as time went on and technique was improved.

by the equation:

$$Q - R = \sigma NQdx. \tag{1}$$

The greater it is, the greater the fraction of the number of incident electrons which are intercepted, the greater the probability of being intercepted for any one electron; it is thus a measure of a probability of likelihood, the "likelihood of interception."

The quantity $(Qe - Re)$ is "missing current"; it is the amount by which the current to the collector drops off, when N molecules per unit volume are introduced into the tube. Nothing has yet been said, nothing has even been implied, about the fate of this lost current and about the missing electrons which presumably bore it into the gas. I have, in fact, been using the very neutral word "interception" so as to evade all implications in excess of what the data say, which is, that some of the electrons fail to persist in the beam. Not to suppose that they have been annihilated, there are at least two conceivable things which may have happened to them. They may have made elastic impacts against molecules, bouncing off in new directions, and being thus deflected out of the beam without suffering much change in speed. Or, they may have struck and stuck to molecules moving in other directions than that of the beam. Other possibilities are thinkable; but these are enough to hold in mind for the present.[5]

(The word "absorption" is used by some, especially by Germans, in the sense for which I here use "interception." It seems to me to convey unwanted implications, but there may be differences of opinion on this point. Much the same problem of language occurs in optics. Usually the term "absorption of light" means in practice "departure of photons from a beam of light" irrespective of whether they are actually swallowed up by atoms, or deflected without any loss of energy; but it is rather common nowadays, especially in treating of X-rays, to use "absorption" for the former mode of disappearance only, and "scattering" for the latter. Since it is necessary now to distinguish two kinds of scattering of photons, the complications are beginning to rival those of electronics.)

Adopting either the elastic-impact idea or the adhesion idea, we may visualize this quantity σ in a familiar way. We may conceive of the molecules, for this purpose and for this purpose only, as spheres so constituted that when an electron touches one of them it sticks—or else rebounds, whichever theory we are using. The value of σ is then

[5] Lenard reviewed a number of possibilities, and considered ways of distinguishing them in his brochure *Quantitatives über Kathodenstrahlen*. He made a peculiar distinction between reflection of electrons from molecules, and small deviations of electrons by molecules; it seems to have been suggested by his work on very fast corpuscles.

the value which must be assigned to the cross-section of these spheres, in order to make the calculated values of "missing current" agree with the observed ones.

An elastic-sphere model is also used in the kinetic theory of gases: one visualizes a gas as a flock of spheres, and for their cross-section one chooses the particular numerical value which, when inserted into the kinetic-theory formula for the viscosity of that gas, gives a figure agreeing with the measured viscosity. This is the so-called "gas-kinetic cross-section," which I will denote by σ_0. One should not expect it to be identical with the quantity σ which has just been defined, nor be surprised at finding differences—even differences in order-of-magnitude —between the two. The elastic-sphere model is good for many purposes; but it has its limitations.

The ratio of σ to σ_0 is occasionally used instead of σ as a measure of the likelihood of interception. Much more frequent of usage [6] is the product of this σ by N_1, the number of molecules in a cc. of a gas at 0° Centigrade and one mm. Hg ($N_1 = 3.56 \cdot 10^{16}$). So also is the reciprocal of $N_1\sigma$, the so-called "mean free path" of the electrons under the stated conditions, zero Centigrade and one millimetre pressure. It should be called "mean free path for interception," but the qualifying word is usually left out. The reciprocals of $N\sigma_0$ and of $N_1\sigma_0$ are also frequently used as standards of comparison, sometimes with the name "gas-kinetic mean free path." Since the concept of mean free path is used quite often in stating the results of these experiments, I will give the reasoning whence follow at once its definition, and its relation to the quantity σ.

Returning to equation (1), rewrite it thus:

$$dQ = -\sigma NQdx. \tag{2}$$

Here the quantity $(Q - R)$, the number of electrons lost per unit time from the beam between the planes x and $x + dx$, is written as $-dQ$, the negative of the difference between the numbers which in unit time cross the planes $x + dx$ and x respectively. Integrating, we get:

$$Q_1/Q_2 = \exp\,[-N\sigma(x_1 - x_2)] \tag{3}$$

for the ratio between the numbers crossing any two planes separated by the distance $(x_1 - x_2)$.

For simplicity, suppose that it is at the plane $x = 0$ that the corpuscles enter the gas, and denote by Q_0 the number entering per unit time. Then the number $Q(x)$ reaching any plane x is this:

$$Q(x) = Q_0\exp(-N\sigma x), \tag{4}$$

[6] Especially by Ramsauer, by Brüche, and other Germans generally.

and this is the number of electron-paths which extend unintercepted through the distance x measured from the plane $x = 0$. Out of these, the number which are terminated between the planes x and $x + dx$ is this:

$$-dQ = N\sigma Q dx = N\sigma Q_0 \exp(-N\sigma x)dx \tag{5}$$

and this is the number of electron-paths which, measured from the plane $x = 0$ to their termini, have lengths between x and $x + dx$. Multiply it by x, and you have the sum of the lengths of all these paths. Integrate this product $xN\sigma Q dx$ from $x = 0$ to $x = \infty$, and one has the total length of the unintercepted paths of all the Q_0 electrons; divide the integral by Q_0, and one has their mean length l, the "mean free path for interception":

$$l = \int N\sigma x.\exp(-N\sigma x)dx = (N\sigma)^{-1}, \tag{6}$$

and this is the reason for giving the name "mean free path" to the reciprocal of $N\sigma$. As for the reciprocal of $N_1\sigma$, it is the value of mean free path at zero Centigrade and one millimetre pressure; it may be denoted by l_1:

$$l_1 = (N_1\sigma)^{-1}. \tag{7}$$

Though everywhere along this train of reasoning the paths were supposed to be measured from the plane $x = 0$ where I said that the corpuscles entered the gas, the result is not restricted. No matter where the plane, from which the paths are measured (so long as it lies in the gas), the mean of their lengths from that plane to their various terminations has the same value $(N\sigma)^{-1}$. It follows that if these so-called "interceptions" are elastic collisions, from which the electrons rebound with practically the same value of speed as they had beforehand, the mean-free-path from one collision to the next should likewise be equal to $(N\sigma)^{-1}$. But this is a deduction which we can hardly hope to check by simple experiments on a beam of electrons, since after its first collision a corpuscle quits the beam. Of course, if the "interceptions" are adhesions of electrons to molecules, there is no sense in making this extension.

Something must now be said about the relation between these "mean free paths" of electrons, and the quantity called the "mean free path of the molecules of the gas." Even if σ were equal to the gas-kinetic cross-section σ_0—even if the molecules behaved towards one another as elastic spheres of radius $\sigma_0/\sqrt{\pi}$, and towards electrons as elastic spheres of the *same* radius $\sigma_0/\sqrt{\pi}$—the mean free path of a molecule between collisions with its mates would not be the same as the mean free path of an electron between collisions with molecules. For, conceiving an electron

as a mere point (as we are regularly doing); if it is to hit a molecule M, the direction of the motion of its centre, which is itself, must be pointed towards M. But if instead of an electron it is another molecule M' which is to hit M, the sufficient condition is that the direction of motion of the centre of M' should be pointed towards a sphere of twice the radius, four times the cross-section of M or M'. Merely on this account, the mean free path of a molecule among similar molecules should be only one-fourth as great as it would be, if the moving particle were shrunk to a point. Another allowance must be made for the fact that all the molecules of a gas are in motion, although their motions are so slow that relatively to a free electron they may be viewed as stationary. I shall not derive the formula for this latter allowance; but the net result of both may be expressed in this way: the ratio of the mean-free-paths of an electron and a molecule, in a given gas, should be $4\sqrt{2}$ if the ratio σ_0/σ of the gas-kinetic cross-section to the cross-section for electron-impact were equal to unity. This result however is based on so very specific and in part fallacious assumptions, that I should not have treated it at such length, but for the fact that it is more or less the custom to divide the mean-free-path for interception of electrons by $4\sqrt{2}$, and compare the result with the mean free path of molecules as the kinetic theory of gases supplies it from the viscosity of the gas. This amounts in practice to using still another measure of the "likelihood of interception": to wit, the ratio $4\sqrt{2}\sigma_0/\sigma$.

Doubtless it seems that I have spent excessive time in talking of these measures of the likelihood of interception. There is however, an unimpeachable reason for dwelling on the topic: the likelihood is the only thing which *can* be measured. There are no critical "intercepting potentials" like ionizing or resonance potentials; there are no specific energy-values of the impinging electrons at which interception abruptly starts; there is nothing in the nature of sudden "onset" to be detected. The probability of the effect is the physical reality, it *is* the effect; and its relation to the speed of the electrons is the only quality available for study. Unless we know precisely how we are defining it, we know nothing. Also we shall soon be looking at experiments which yield values for quantities much like the σ of interception, and yet not quite the same; it will be necessary to discriminate with great care. But let us first consider the direct experiments of the type which I have been presuming.

The experiments would certainly be simplest, if the electrons were dashing along with enormous forward speeds, corresponding to vis viva of the order of thousands of equivalent volts; for then their transverse speeds would probably be negligible, the beam would have little

tendency to spread other than that for which the gas itself is accountable. As early as 1894, Lenard did such experiments with 30-kilovolt electrons (cathode-rays which had emerged from a discharge-tube through a window of thin metal foil). A few years later, he added data obtained with slower electrons, and the work was continued by Becker and by Silbermann.[7] For the 30-kilovolt corpuscles, the cross-section σ is very much smaller than the gas-kinetic σ_0—only a few per cent as great. As the energy of the electrons is decreased, σ rises towards σ_0. All this is illustrated in Fig. 1.

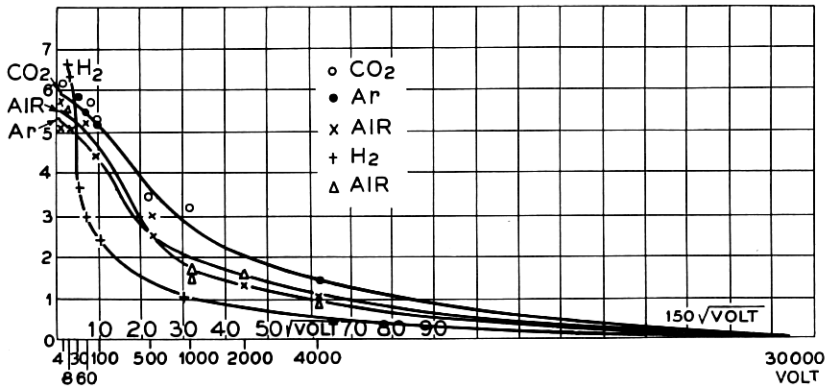

Fig. 1—Cross-section for interception of electrons, plotted for various gases over a wide range of electron-speeds. (P. Lenard, *Annalen der Physik.*)

Obviously, these are not experiments in which the corpuscles are unable to ionize or to excite; quite the contrary. One might be tempted to rush to the other extreme, and guess that all of the electrons missing from the beam have effected ionizations, that the quantity σ of Lenard's experiments is a measure of *likelihood of ionization;* but in the present state of knowledge, this would be going too far. It is important, however, that for the *fast* electrons σ turns out to be proportional to the atomic number of the gas, if this is monatomic; and to the sum of the atomic numbers of the atoms constituting the molecule, if the gas is diatomic or triatomic. This sort of rule suggests that interception of fast-flying corpuscles is due either to the nuclei of the atoms, or to some action of the bound electrons of the atoms in which they all are equally potent, however tightly or loosely they are bound.[8]

[7] References are given at the end of the paper.

[8] Silbermann (dissertation, Heidelberg, 1910) and A. Becker investigated a large number of organic compounds, using fast electrons; and they found that the σ of each of these molecules (some of them composed of five to twenty atoms) could be predicted accurately, simply by adding together the values of σ for the constituent atoms as determined by experiments on simpler gases.

In his latest experiments Lenard went down to electron-speeds so low that he was working near, or even below, onset of ionization; but instead of dwelling on these, I will take up the experiments which are designed primarily for the study of slow electrons—experiments, the first of which were made in Lenard's own laboratory by his associates, H. F. Mayer and C. Ramsauer. They tried in somewhat different ways to realize in practice the ideal scheme of apparatus which in the last few pages I have been taking for granted. Before depicting their devices, I revert for a moment to equation (4) above.

Suppose that the collector is located at the distance x from the aperture where the beam of Q_0 electrons per second enters the gas: the number Q of electrons and the charge Qe reaching it in a second should conform to the epuations:

$$Q = Q_0 \exp(-N\sigma x), \tag{8}$$

$$\log(Qe) = \log(Q_0 e) - N\sigma x. \tag{9}$$

Thus on plotting the logarithm of the collector-current against x one should get a straight-line graph, and *the slope of the line should give the value of* $N\sigma$, therefore the value of σ when the density of the gas is known. It should suffice to slide the collector along the direction of the beam, and plot the logarithm of the current against the distance through which it has slid, measured from any arbitrary zero. Or alternatively, one might keep the collector stationary at some fixed distance x_0 from the point of entry, and vary the density of the gas. Plotting logarithm of current against N, one should get a straight-line graph, and the slope of the line should give the value of $x_0\sigma$. It is then unnecessary to worry about the possible presence of residual vapors of unvarying density not recorded by the pressure-gauge, for they would contribute only an additive term to N, not affecting the slope of the line.

It must be granted that the interpretation of the data is seldom quite so simple. The quantity Q_0 may vary with the density of the gas; some observers determine the total emission of electrons from the source (or something which they take to be proportional thereto) for each value of N separately, and plot the logarithm of the ratio of Qe to this latter as function of N. The beam may diverge even in a vacuum, or what the experimenter takes to be a vacuum; some measure Qe twice for each value of x, once with a vacuum and once with gas, and plot the logarithm of the ratio of the two as function of x. Mayer varied both N and x and combined the results in the hope of thus eliminating the effects both of the divergence of the beam in a vacuum, and of residual gases.[9]

[9] It is not always easy to make out from a paper just what procedure the observer has followed, nor how far he has traced the curves of Q vs. x or Q vs. N.

(I pause to point out the relation between formula (8) and the earlier formula (1). The first two terms in the Taylor expansion of e^{-y} being $(1 - y)$, one may write instead of (8),

$$Q = Q_0 - Q_0 N\sigma x, \tag{10}$$

which is formula (1).)

The experiment of Ramsauer acquired instant fame, because the data which he got with argon were of a nature totally unexpected,[10] and caused immense surprise.

His apparatus is a metal box, partitioned into chambers, the party-walls of which are pierced with slits delimiting a narrow path curved in the form of a circle. Details are different in the different boxes which he used at various times, and in those which several other physicists—

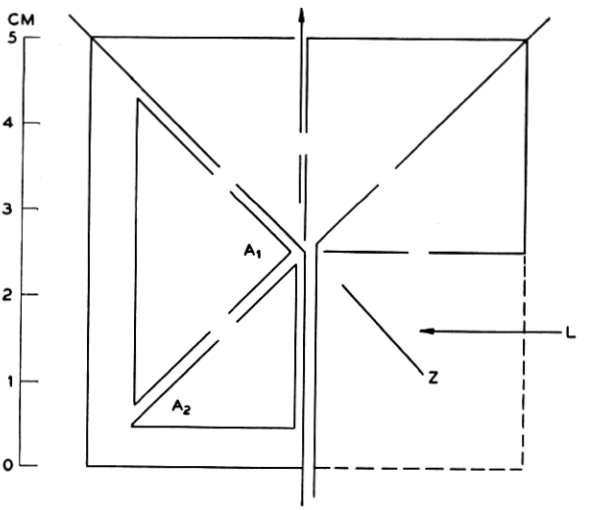

Fig. 2—Ramsauer's apparatus for measuring the cross-section for interception. (*Physikal. Zeitschrift.*)

Maxwell, Brode, and T. J. Jones among them—made after the pattern of his; but a fair idea of all is given by Fig. 2. Photoelectrons [11] escape from the metal plate at Z, and are accelerated to the speed desired by a potential-rise from Z to the walls of the box. The electron-beam consists of corpuscles sweeping around in circles so centred and so proportioned that they pass through all the slits. It is of course a magnetic

[10] This was first disclosed in Mayer's paper from the same laboratory, but Mayer yields to Ramsauer the credit of having noticed it sooner.

[11] Some of the American physicists used thermionic electrons instead; in certain experiments the filament replacing Z is encased in a coaxial cylinder with a narrow slit, from which electrons escape after receiving the energy corresponding to the potential-rise from filament to cylinder.

field, perpendicular to the plane of the drawing, which causes them to revolve so. This field limits the speeds of the electrons in the beam to a certain range, which may be narrower than the range over which the speeds of the electrons emerging from Z are spread.[12] It has a second purpose, which we shall see directly. The electrons are collected in either of the chambers A_1 and A_2, alternate use of which enables the observer to vary the distance x figuring in equation (8). Mostly, however, it is the density of the gas which is varied.

If there is gas in the box, electrons which by striking molecules are deflected even a little go to one of the partitions, and vanish from the beam. So also do electrons which strike molecules and stick to them; even were one to adhere to a particle of molecular size which happened to be moving in the direction tangent to the beam, the resulting massive ion would travel in a path with a different curvature, and fall against a wall. Again, if an electron should suffer a loss of kinetic energy without losing its freedom or its direction of motion, it too would be eliminated from the beam; its path would be more curved after the impact than before, and it would miss the slits. Again, if by an ionizing impact a fresh electron should be ejected from a molecule, it would be moving more slowly than those of the primary beam, and could not stay with them. Finally, if an electron were bounced out of the beam by an elastic impact with a molecule, it could not be bounced back in in again by fewer than two additional collisions, and these it would be most unlikely to make. Clearly, the quantity σ of which this apparatus gives the value is very stringently defined!

Suppose now the magnetic field omitted, and the slits and chambers of the device of Fig. 2 all arranged along one straight line. This gives another well-known type of apparatus. The first of this kind was the one which Mayer used, but I choose for representing here the one designed by T. J. Jones (Fig. 3). The electron-beam, consisting of electrons which emerge from the filament F and are accelerated by a rise of potential between F and the screen D_2, is shaped by the sequence of slits which is shown in the sketch, and enters the chamber B through

[12] Ordinarily the magnetic field is so adjusted, that the range of electron-speeds aforesaid is centred at the value which is the most probable speed of the electrons. The corpuscles which have come out of the source and have been accelerated to the first slit have a certain distribution-in-speed with a maximum at some special value, say u_0; the range selected by the magnetic field has u_0 as its center. However Ramsauer and Kollath found that they could not do this with electrons having less energy than 0.45 equivalent volt; they then adjusted the field so as to select ranges of speed lower than that which included the maximum, and were able to extend their experiments as far down as to electrons of 0.16 equivalent volt. The use of the magnetic field has the incidental advantage, that the values of electron-speed deduced from its value and from the radii of the circular orbits are correct even if there are contact-potential differences in the box—something which cannot be said for those deduced from the voltage applied between box and filament.

the slit S_1. The part of the beam which is not intercepted goes on into the chamber C. In the notation of equation (8), the current Qe is that reported by the galvanometer G_2, the current Q_0e is the sum of those reported by G_2 and the other galvanometer G_1; the distance x is measured from the slit S_1 to the pair of slits S_2S_3, and therefore has a constant value x_0, while N is varied by admitting or withdrawing gas. In certain experiments of Brode and in those of Rusch, the electron-beam passes through a metal-walled channel—as though the slits S_1 and S_2 were circular apertures, the opposite ends of a metal tube. In the similar devices of Mayer and of Maxwell, the distance x is varied by sliding the chamber C back and forth, thus lengthening or shortening the chamber B; for which purpose, B and C are made of lengths of tubing of which the latter telescopes into the former.

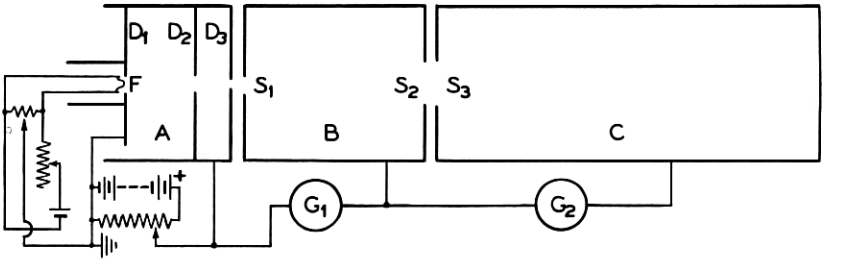

Fig. 3—Apparatus for measuring cross-section for interception, of the "Mayer" type. (T. J. Jones, *Physical Review.*)

Comparing this now with Ramsauer's device, one sees that in either apparatus, electrons which are considerably deflected in collisions fail to reach the collector. However, among the various effects which were listed in the last paragraph but one, which a molecule might conceivably produce, there are some which would cause electrons to quit the beam as defined in the Ramsauer apparatus, but not as defined in Mayer's,—for instance, a corpuscle which had lost much of its speed without suffering change of direction of motion would go right on into C of Fig. 3, as though it had had no encounter at all, while in the Ramsauer scheme it would figure among the missing. The quantity σ determined by a scheme of Mayer's kind is thus essentially different from the σ determined by one of Ramsauer's kind; and indeed any change in detail of either, any widening of the slits for example, should involve a change in the meaning of the σ which the experiment reveals—to each apparatus, its own cross-section of the molecule! Thus by applying a retarding-potential between the slits S_2 and S_3 of Fig. 3, one might withhold from the collector such electrons as had

suffered much loss in speed but little deviation,[13] and the σ measured by the so-modified device would approach more nearly to that of Ramsauer's. Modifications like this might conceivably entail enormous changes of the relevant cross-section. But it happens that they do not —a very important fact [14] in itself, illustrated by Fig. 7 (for mercury vapor); and therefore the results of all the work can be summarized *en bloc.*

I begin with the surprising fact, of which the disclosure excited so wide an interest in this field. Argon was the gas on which the dis-

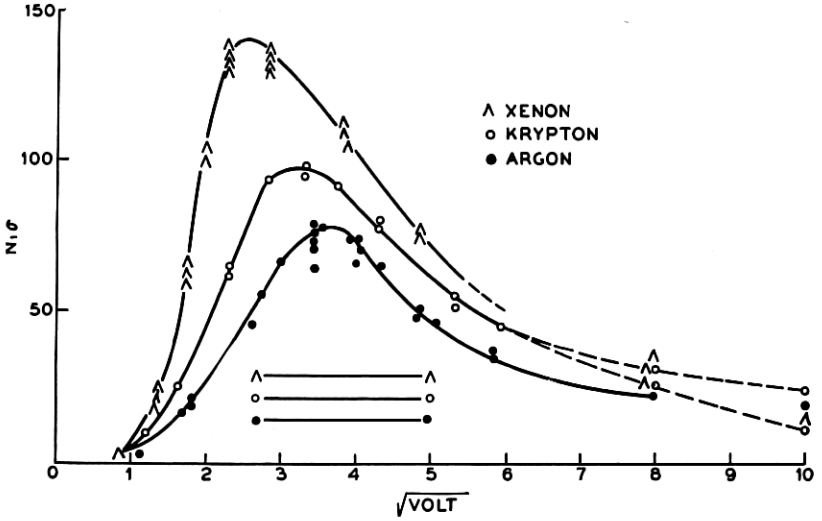

Fig. 4—Cross-sections of atoms of three of the noble gases, determined by Ramsauer with the scheme of Figure 2. (*Physikal. Zeitschrift.*)

covery was made by Ramsauer, and checked by Mayer (and a little later by Townsend and Bailey, in an entirely different way; but since krypton and xenon show even more strikingly the "anomaly"—as it used to be called, and should be called no longer—I present the curves for all three of these gases together (Fig. 4). They are curves of $N_1\sigma$ (the reciprocal of l_1) versus the speed of the electrons.[15]

[13] This in effect was done by Mayer, whose collector was shaped like a cup covered over with a pair of parallel gauzes; he made the cup and the inner grid a volt or two more negative than the outer gauze. Notice that this is a scheme for detecting critical potentials for onset of inelastic impacts.

[14] Moreover, a distinctly puzzling fact, especially as sometimes the σ obtained by Ramsauer's method appears to be less than that obtained by Mayer's (see Fig. 7, and the paper of M. C. Green).

[15] In this department of electronics it is the custom to use as independent variable, not the kinetic energy of the electrons expressed in equivalent volts, but the speed of these corpuscles expressed either in centimetres-per-second, or (more commonly) in "square-roots-of-equivalent-volts," i.e. in a unit equal to $5.94 \cdot 10^7$ cm./sec. I do not know of any valid reason for this anomaly of usage, except insofar as it may be found that the corresponding curves for protons and other ions display similar features at equal speeds but not at equal energy-values.

Going towards lower speeds from the highest here represented, one sees that the curves are ascending. This is to be expected; they are the prolongations of the curves for fast electrons exemplified in Fig. 1; the cross-section for interception is steadily increasing as the corpuscle-speed diminishes, the atoms (these are monatomic gases) are bigger obstacles for slow electrons than for fast. But instead of always ascending, *they pass through maxima and sink as the electron-speed is further lowered.* This is the surprise. The atoms of argon, krypton and xenon are smaller obstacles for very slow electrons than for moder-

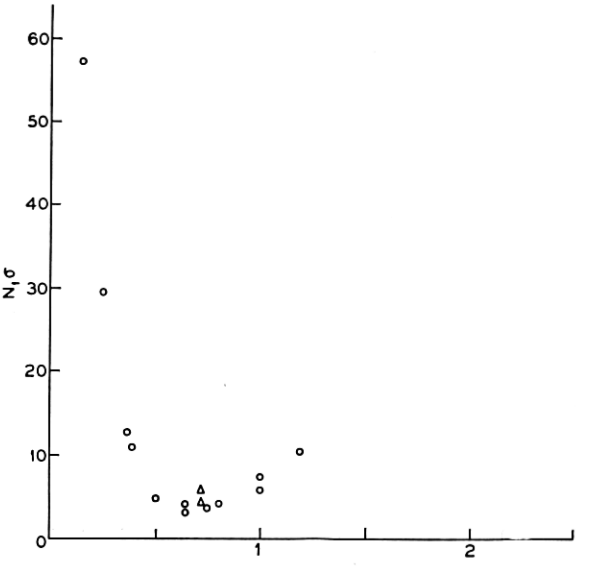

Fig. 5—Cross-section of xenon atom, for very low values of electron-energy. (C) Ramsauer, R. Kollath, *Annalen d. Physik.*)

ately slow ones. Below the maxima, there are minima and renewed ascents; these are very late discoveries of Ramsauer and Kollath, just confirmed by Normand and Brode; that of xenon is illustrated by Fig. 5.

The ordinates of the horizontal dashes in Fig. 4 are the values (multiplied by N_1) of σ_0, the gas-kinetic cross-sections of these three kinds of atoms. One sees that σ is several times greater than σ_0 at the maximum of each curve, several times smaller than σ_0 at the minimum. It was thought formerly that σ_0 should be the limit which σ approaches as the electron-speed approaches zero, and Lenard's early results with fast electrons seemed to sustain the notion; it perished at the advent of these data.

For helium and neon, on the other hand, the cross-sections vary but little over the energy-range from 1 to 40 equivalent volts, though for each there is a gentle flattish maximum. Below one equivalent volt, σ for neon falls gradually and smoothly as far as the limit (0.16 e.v.) of Ramsauer and Kollath's data, while the curve for helium has a couple of wiggles. Normand and Brode find a minimum in the neon curve.

It seems odd to speak of methane (CH_4) among the monatomic gases; but its σ-curve is of the same kind as those of the three massive noble gases, displaying a sharp maximum [17] near 8 equivalent volts. One notices however that if the four electrons of the four H atoms were to join the four outer electrons of the C atom, they could form a shell of eight to simulate the closed outer shell of an inert-gas atoms. But the noble gas most closely simulated should be neon, and neon does not show the high sharp maximum.

The other monatomic gases are the vapors of the metals. As in the measurements of their resonance and ionizing potentials, they are difficult to handle. There is an extra difficulty, over and above those which beset the seeker after critical potentials: the measurer of σ must know the density of the gas, therefore the vapor-pressure of the metal with which he is working. But vapor-pressures change so rapidly with the temperature, that this must be determined very carefully. Even after one has determined the temperature with exceeding care, one may find on searching the literature that the density-vs-temperature curve has never been reliably determined. The data for mercury are by far the most abundant; there are a few for cadmium and zinc, which belong to the same column of the periodic table (Fig. 6). All three have similar cross-section curves, which except for a little hump near 40 equivalent volts rise steadily with fall of corpuscle-speed. I reproduce an additional curve for mercury (Fig. 7), for it illustrates the smallness of the difference between the σ of the Ramsauer method and that of the method of Mayer. The "method of Part I" is substantially Ramsauer's; the "method of Part II" involved the use of the tube shown in Fig. 3.

The four familiar members of the alkali-metal column were subjected to experiment by Brode; each of the four curves of $N_1\sigma$ versus electron-energy has a sharp maximum near 1 or 2 equivalent volts, and this maximum is astonishingly high—greater than 1000 for all four, almost

[17] R. B. Brode (*P. R.* (2), **25**, 636–644; 1925). Akesson is said to have discovered this maximum, even before Ramsauer's research (*Lund Arsskrift*, 1916). This paper of Akesson's is the outstanding example of an article which hundreds cite for one who has seen it. For some reason—the war, very likely—it was never published in any journal enjoying a wide circulation.

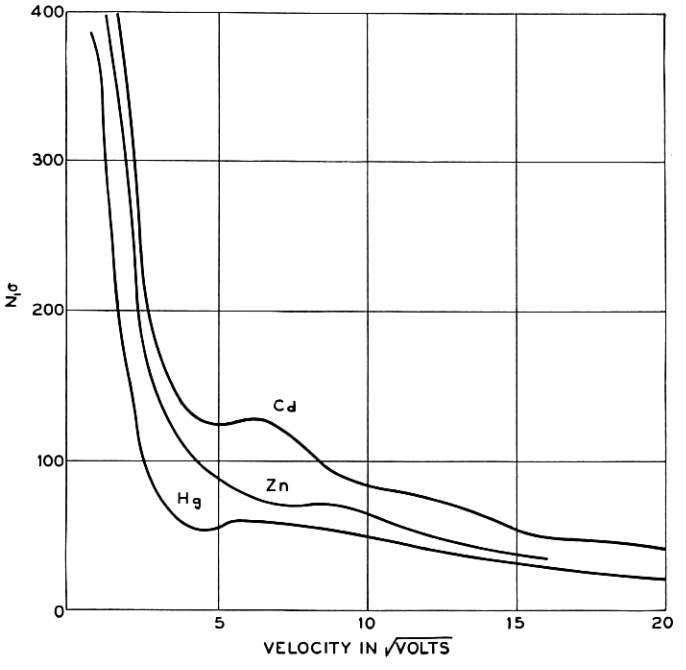

Fig. 6—Cross-sections of metals of the second column of the periodic table. (R. B. Brode; *Physical Review.*)

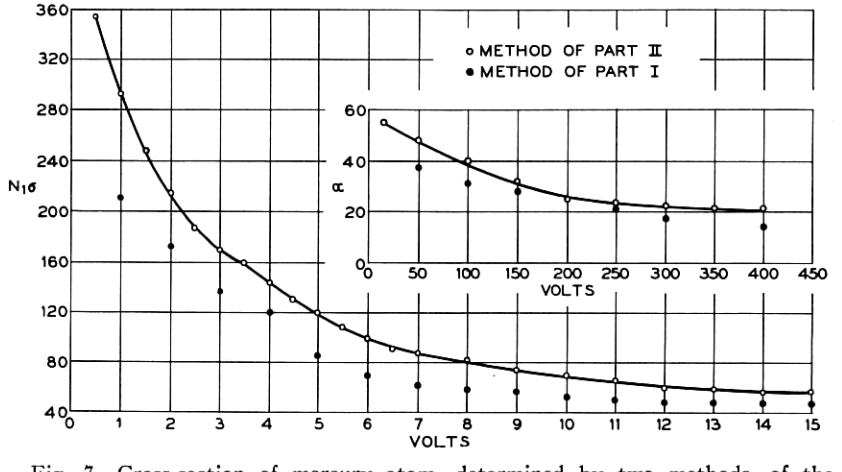

Fig. 7—Cross-section of mercury atom, determined by two methods, of the "Ramsauer" and "Mayer" type ("Part I" and "Part II") respectively. (T. J. Jones, *Physical Review.*)

2000 for cæsium. Dividing these values by N_1, we see that this means that for electrons of the corresponding speed, the atom is as great an obstacle as would be a sphere of cross-section 3.10^{-14} cm^2., of radius 10 Angstroms or more. Sizes such as these, when compared with the σ for ionization or with the gas-kinetic cross-section of the atom, are surprisingly large.

The molecules of the common molecular gases also yield curves with maxima, located however at energy-values lower than those at which the peaks for the noble gases stand. Brode in 1925 discovered a minor maximum for nitrogen at some 20 equivalent volts; but the really important ones lie much lower, those for hydrogen and nitrogen somewhere between 2 and 3. In Fig. 13 I show a curve for a trimolecular gas, carbon dioxide; Ramsauer has lately found that to the left of the point where this curve is cut off in the graph, it rises rapidly again. Oxygen shows a sharp minimum near 0.25. One sees that the so-called "anomaly" of argon is nothing anomalous at all; it is merely an example unusually conspicuous of a feature which atoms and molecules generally display.

Observations on the Scattered Electrons Themselves

Recall the classical experiment of Franck and Hertz—the one which led to the discovery of "inelastic impacts" of electrons against atoms, the discovery of the transfers of energy from electrons to atoms which result in excitation. There are three electrodes in a tube: a filament, the source of electrons—a grid, at a potential V volts higher than the filament—a plate beyond the grid, at a potential lower than this latter by a small and constant amount. The number of electrons arriving at the plate is plotted as function of V, and certain "breaks" are seen in the curve; these fix the location of the critical energy-values of the electrons, at which various modes of excitation first become possible.

Now this is not much different from the experimental method of Lenard, of Mayer and of others, in the work which I have just been citing; only, there is an important difference in aim; much more attention was paid by Franck and Hertz to the breaks, and the rôle of the retarding-potential between the plate and the grid. Franck and Hertz were studying electron-scattering with especial regard to the distribution-in-energy, and to the energy-losses, of the scattered corpuscles. In other work of theirs, they had auxiliary collectors off to one side from the grid, thus in effect studying scattering at large angles. It is further and more elaborate work of this sort which we have now to consider.

One scheme of apparatus was realized first by E. G. Dymond. I show in Fig. 8 a slight modification, set up by G. P. Harnwell. On the left, the electrons come from a filament contained in the cylinder *C*, are accelerated through a slit (1) in the cylinder and a second slit (2) in the front wall of a chamber beyond. (For arrangements of this sort, the word "electron-gun" has become the standard metaphor.) They meet the molecules in the center of the tube, and those which are scattered in directions passing through slits 3 and 4 go through these

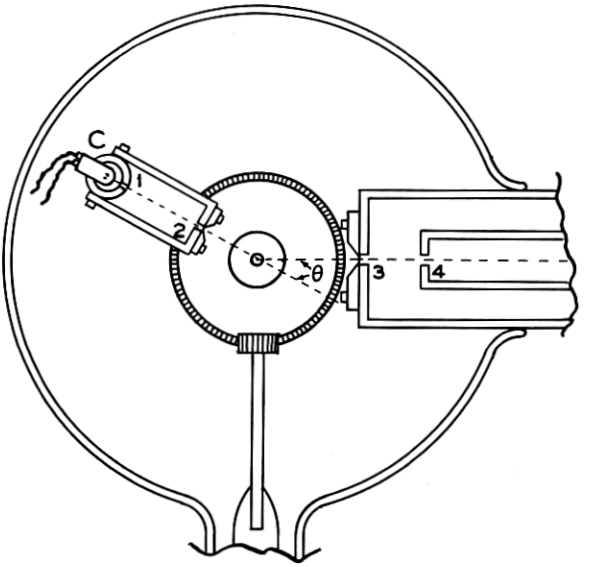

Fig. 8—Harnwell's apparatus for studying scattered electrons. (*Physical Review.*)

slits (unless they make further collisions) and onward into the "analyzer." The electron-gun can be revolved around the axis cutting the plane of the paper normally at 0, thus making it possible to study scattering as function of angle.

In the analyzer there is a region pervaded by a field, and beyond it a stationary collector, to which electrons go if they are suitably deflected by the field,—as in many a well-known type of analyzer used for identifying ions, for instance Aston's or Dempster's for finding isotopes. There, however, it is the charge-to-mass ratio of the ions which is computed from the strength of the deflecting field which sends them to the collector, their kinetic energy being taken as known. Here it is the energy of the electrons which is computed from the strength of the field, their charge-to-mass ratio being accepted as known. One plots the collector-current against the field-strength, and then, translating

the later variable into electron-energy by means of the known relation, one gets the distribution-in-energy of the scattered electrons. (Incidentally, in Harnwell's apparatus and in that of MacMillen the deflecting field was electric; in Dymond's magnetic.)

Typical data of Harnwell's are shown in Fig. 9; these are distribution-in-energy curves for electrons scattered by helium, their initial energy having been 75 or 150 equivalent volts (curves on left and right, respectively). First, one sees that the great majority of those which go

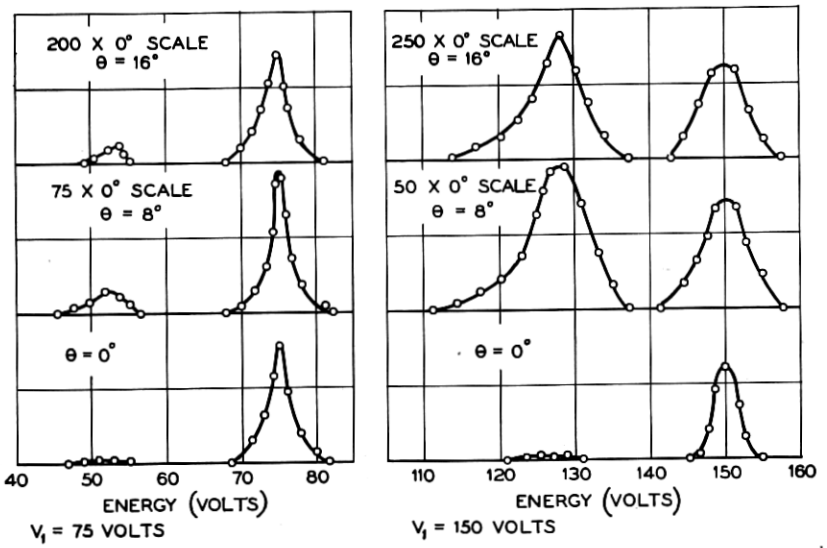

Fig. 9—Distribution-in-energy of electrons scattered from helium atoms, as determined by Harnwell. (*Physical Review.*)

through nearly undeflected retain their energy. Then, the electrons which are deflected through angles in the neighborhood of 8° are very much fewer (notice the change in the scale of the axis of ordinates) but among them, those which suffer a certain energy-loss are relatively more numerous. The electrons deflected at 16° are fewer yet, but among them those which suffer the same energy-loss are relatively plentiful. With 150-volt corpuscles one sees the same behavior, with differences in detail which I leave to be read from the curves. As for this peculiar value of energy-loss, its "mean value from a large number of observations is 22 volts"; one recalls that the resonance-potential of helium is 19.6, and that there are other critical potentials of inelastic impact ranging from this value upwards.

Curves obtained by Dymond and Watson, also for helium, appear in Fig. 10. The angle of deflection is about 10°, and the experiments

were performed with 102-volt, with 226-volt and with 386-volt electrons. The double-pointed peaks bear witness to two distinct amounts of energy-loss frequently occurring; one maximum lies between 21 and 22 equivalent volts, the other is somewhat greater. Now the minimum amounts of energy which the helium atom can absorb, or in other words the energy-values of its lowest excited states, are 19.77 and 20.55 equivalent volts; and there are many others distributed between the upper of these and the ionizing-energy, which last is 24.5. It seems natural to

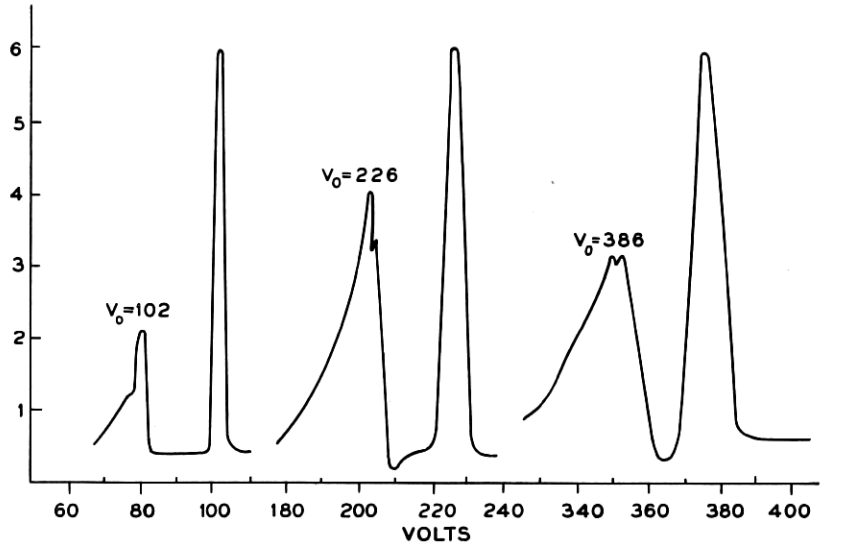

Fig. 10—Distribution-in-energy of electrons scattered at 10° from helium atoms, as determined by Dymond and Watson. (*Proc. Roy. Soc.*)

ascribe the less-displaced of the two points of the shifted peak to processes of excitation, the other to ionization; but one is tantalized to note that the peaks are not located quite accurately enough to settle this. Dymond and Watson find that as the angle of deflection is increased, the electrons scattered with undiminished energy take more and more the lead over those which contribute to the shifted peak.

Still other curves for helium can be seen in the article of MacMillen. Analyzing the 50-volt electrons scattered at 10°, he was able to plot a curve displaying no fewer than three distinct maxima, not counting the great one corresponding to the elastically-reflected corpuscles—evidence, therefore, of three distinct and distinctive energy-transfers. The most frequent of these he estimated as amounting to 21.50 equivalent volts, with a probable uncertainty of 0.15; the others are

greater by 2.13 and by 2.95 equivalent volts. The accuracy is such that one may attempt to compare them with the energy-values of the excited states of the helium atom, but here there is a disappointment—the agreement is not so good as one would like. MacMillen is disposed to think that the value 21.50 should be corrected to 21.12 and the two others shifted equally, whereupon the first would agree accurately and the two others passably with the energy-values of known excited states. But these three do not comprise the two lowest of the excited states, the 19.77 and 20.55-volt levels which I mentioned above; it would then be necessary to assume that these are much less likely to be attained than three of those above them, which seems surprising but not impossible. At any rate it is evident that the time has arrived for experimenting in ways which permit of locating the shifted peaks with the highest accuracy possible.

Continuing with Harnwell's data: neon yielded a set of curves very like those of helium, except that the mean value of the energy-loss, deduced from the separation of the pair of peaks corresponding to the pairs in Fig. 9 amounts to some 18 equivalent volts; this is predictable. Molecular hydrogen displayed an energy-loss of 12.3 equivalent volts; but the most striking feature of the curves is the prominence of the peak formed by electrons which have lost that amount of energy—indeed, with 75-volt electrons, even those which go through nearly undeflected include a larger proportion of such, than of corpuscles which have retained their capital intact. Harnwell made measurements on nitrogen also, and on a mixture of molecular with atomic hydrogen, this being supplied from a discharge-tube in operation; and I reproduce as Fig. 11 his graph showing the distribution-in-angle of electrons scattered *without* loss of energy, the hollow circles relating to molecular hydrogen, the dots to the mixture.[18] The corresponding curves for electrons scattered *with* loss of energy lie very close together, and the one marked *C* in Fig. 11 represents them both. MacMillen traced similar but not exactly concordant curves for hydrogen, and others for helium and for argon. In his data also, electrons scattered through small angles predominate more and more, the greater their initial speed; and it is rather surprising to find how large a proportion of the corpuscles which have lost energy to helium atoms continue nevertheless with little or no deflection.

Somewhat earlier, Jones and Whiddington had studied the distribution-of-energy of electrons after passage through hydrogen, confining

[18] The continuous curves marked *A* and *B* are graphs of predicted distribution-curves deduced (for atomic hydrogen) from the assumptions of wave-mechanics by Born. The ordinates of all the curves, experimental and theoretical alike, have been adjusted so that all five intersect at 5°.

their observations however to those which had been deflected only a little or not at all. They found that many suffered an energy-loss of about 12.6 equivalent volts, evidently the same which Harnwell was later to observe. Arnot used Dymond's method in a study of mercury vapor; he detected energy-losses corresponding to excitation and ionization, and traced curves resembling those of Fig. 11. Rudberg, working with nitrogen, and likewise concerning himself only with

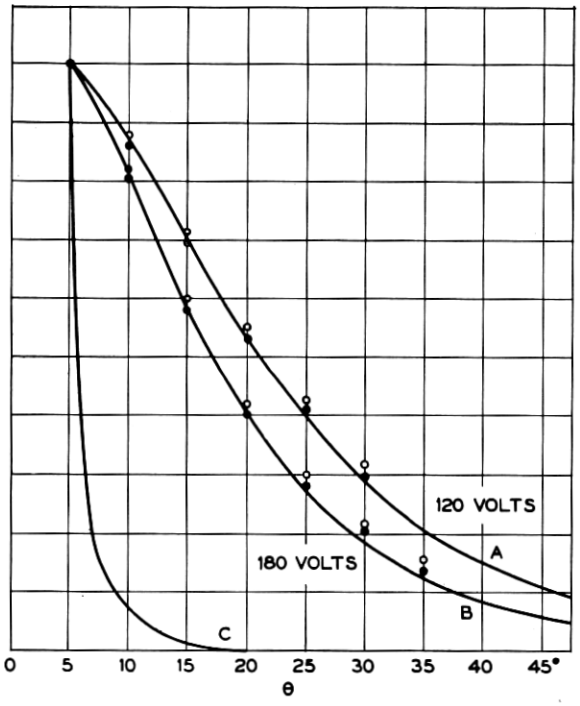

Fig. 11—Distribution-in-angle of electrons scattered from molecules and atoms of hydrogen. (G. P. Harnwell, *Physical Review.*)

electrons which were practically not deflected at all in their collisions, obtained curves with maxima remarkably sharp, indicating several distinct and very precisely determined energy-transfers, the two most prominent amounting to 12.78 and to 9.25 equivalent volts.

Yet another device is that of R. Kollath, which is much simpler than Harnwell's, but functions only for one small range of angles of scattering; it is shown in Fig. 12. The primary electron-beam passes through the slits B_1 and B_2, then onward into the collecting-chamber A; those corpuscles which are scattered at angles between (roughly) 87° and 93° are able to pass between the flat metal rings L of which one

sees the traces on the plane of the paper, and go on to the annular collector K; those which are deflected through other angles are caught by the rings. A potential-drop from the rings to the annular collector precludes from reaching this the electrons which in being scattered have lost more than 15 per cent of their initial energy, so that the ratio of the currents to K and A is a measure of the proportion of the

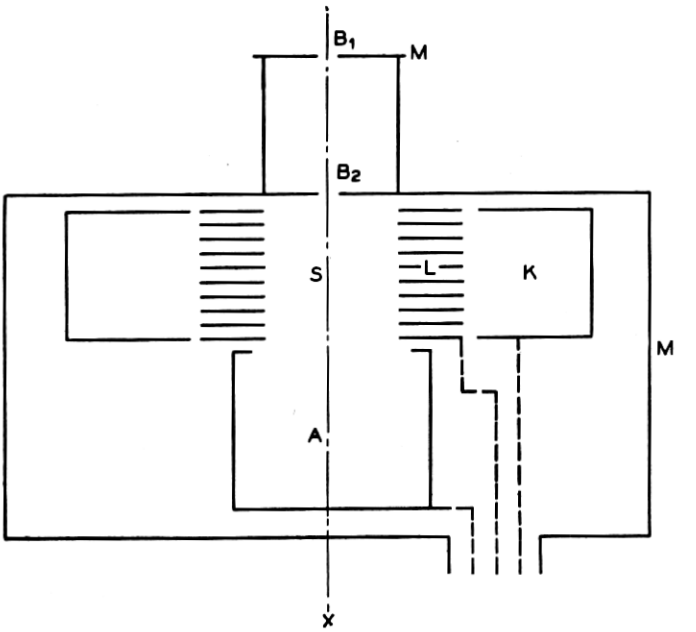

Fig. 12—Kollath's apparatus for determining amount of scattering at angles near 90°. (*Annalen d. Physik.*)

primary electrons, which in traversing a (known) distance through gas of a (known) density are deflected without more than the stated loss of energy through angles within 3° of a right angle. Measuring the ratio at various pressures of gas, Kollath determined the corresponding cross-section for a number of gases. The continuous curves of Fig. 13 are those which he obtained for three of them; the broken curves represent the intercepting cross-section as found by Ramsauer, with ordinates reduced in the ratio 1 : 20. One sees that for each gas the two cross-sections vary in much but not altogether the same way.[19]

I must quote the results of the work of Langmuir and Jones, though

[19] It happens that the ratio 1: 20 is about the ratio which the electrons received by the collector K would bear to all the scattered electrons, if the distribution-in-angle of these were isotropic—which of course is not necessarily so.

the method which they invented is so extremely different from any of those by which the foregoing data were acquired, that in this place I cannot give anything like a full account of it. Briefly: the gas is in a metal cylinder having a filament running along its axis and metal plates

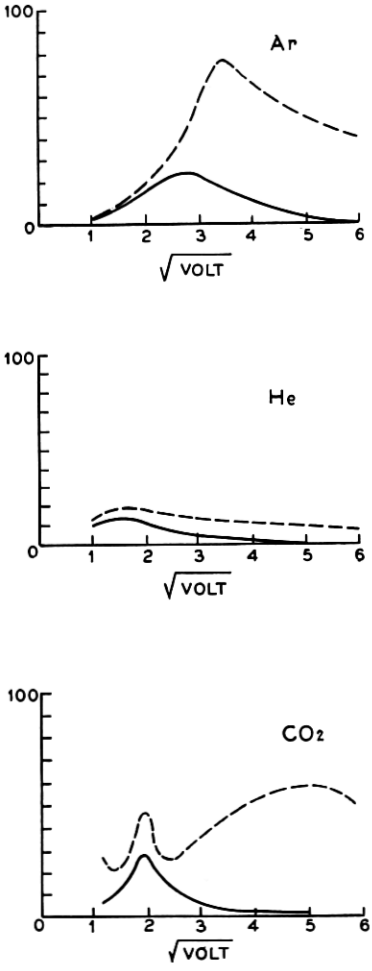

Fig. 13—Broken curves: cross-sections by Ramsauer's method. Continuous curves: cross-sections for scattering at angles near 90°, by Kollath's method (see text). (*Annalen d. Physik.*)

which almost close its ends. One of these end-plates is raised to a potential some fifty or a hundred volts above the filament; and so dense is the electron-current pouring out of this latter, that almost the whole of the gas in the cylinder becomes violently ionized and shining,

and assumes the potential of the plate. I say "almost all" of the gas; a narrow cylindrical sheath about the wire remains comparatively dark, and between the wire and the outer frontier of this sheath the entire potential-rise is spread. Having traversed the frontier, the electrons shoot into the luminous zone of the gas with the energy corresponding to the full potential-rise from the filament to the end-plate. It is as though the boundary of the sheath were a grid connected to the plate; the discharge itself creates its own impalpable grid. The method, then, consists in measuring the current into the cylinder over a range of values of the potential thereof, beginning when the cylinder is at the same potential as the filament and the only electrons which can attain it are those which come clear through the luminous zone without deflection or loss of energy, and ending when it is at the same potential as the end-plate and the luminous gas (or at any rate when it is well above the filament) and electrons can reach it despite their collisions en route. By analyzing the shape of the curve, Langmuir and Jones are able to deduce the values of the cross-section for interception for the various gases they tested, and values of several other things as well; but the analysis is intricate. I shall therefore say only that for the gases neon, hydrogen, argon, helium, nitrogen and mercury, and applying to the electrons voltages ranging from 30 to 100, they found for the cross-section values departing by less than ten per cent from the gas-kinetic cross-section σ_0.

Interception of Positive Ions (Atom-nuclei and Charged Atoms)

We consider next the results of experiments like these of the foregoing pages, in which the beam traversing the gas is a stream of positive ions—protons, or atoms of heavier elements lacking each an electron—and the quantity measured is the number of ions disappearing from the beam, or something more or less nearly equivalent. The experiments as yet are few, and mostly not so accurate as those on electron-beams. This is partly because of the difficulty of obtaining steady reliable sources of positive ions—a difficulty which amounts almost to an impossibility, except for alkali-metal ions, and particles issuing from high-voltage discharge-tubes with kinetic energy amounting to thousands of equivalent volts.

The cross-section for interception, σ, is defined in the same way as for electrons—as the ratio $(Q - R)/NQdx$, to return to the notation of equation (1) of this article. But unless the positive ion is a proton, we should certainly not visualize σ as the cross-sectional area of a molecule of the gas; the size of the flying ion itself is involved. The customary procedure is to compute the "radius" R corresponding to the

"area" σ by the formula $R = \pi\sigma^2$; then to divide R into the "radius r_0 of the molecule" and the "radius r_i of the ion," according to some more or less plausible guess; then to compute the value of πr_i^2, and call it the cross-section of the ion. But all such procedures are more or less dubious, whereas the quantity σ always retains its meaning as a measure of the likelihood of interception.

There is a particular mode of interception for positive ions, different from any to which electrons are subject. If an ion passes close to an atom, it may steal an electron to neutralize itself. The former atom becomes of course an ion, but in general it does not acquire the velocity of the former ion, while the latter being neutralized is not perceived even if it continues on its course to the collector. Therefore, the net result of the electron-transfer is the vanishing of an ion from the beam. It follows from quantum-mechanics that the cross-section of the atom for this special sort of interception is greater, the more nearly the energy required to ionize it agrees with the energy required to re-ionize the neutral atom into which the former ion is transformed by the electron-transfer. Consequently, the greatest values occur when the ion-stream consists of ionized atoms of the very gas through which it is being sent.[20]

One would wish, other things being equal, to duplicate with positive ions the apparatus already used with electrons. The best example of a duplication is that presented by Ramsauer and O. Beeck, who used the device of Ramsauer's earlier work depicted in Fig. 2, substituting for the metal plate at Z a metal ribbon painted with an amalgam of mercury with any of the five alkali metals; heating the ribbon, they got a stream of the ions Li^+, K^+, Na^+, Rb^+, or Cs^+. The gases which they used were A, He, Ne, H_2, N_2, and O_2, though of these argon was the only one of which they measured the interception for all five kinds of ions. The range of energy-values extended from 1 to 30 equivalent volts, and over it the value of σ in every case diminished steadily with increasing energy. When different ions were driven through the same gas, the value of σ was found to be greater, the greater the atomic number of the ion; when ions of the same kind were tried in different gases, it was found to be greater, the greater the molecular weight of the gas. All this is as one would expect. The value of R (as defined in the paragraph above) is of the same order of magnitude as the sum of the gas-kinetic radius of the molecule or atom of the gas, and that of the ion.

[20] For the theory, and for a bibliography of the experimental work, see H. Kallmann & B. Rosen, *ZS. f. Phys.* **61**, 61–86 (1930). I shall treat the subject more extensively elsewhere.

Dempster experimented with a scheme which may be likened to Ramsauer's with the final slit halfway around the circle from the initial slit, and all the slits and walls between suppressed.[21] Later it was adopted by some of his pupils, and by Kallmann and Rosen. Various mixtures were used by Dempster and his pupils to produce the ions; some were heated, some bombarded by electrons; one of them, when thus bombarded, emitted protons and H_2^+ ions, a very useful property. When one varies the magnetic field and plots against it the current which passes through the final slit and is captured by an electrometer posted behind, one gets a curve with a series of peaks, one for each kind of ion present.

When the deflection-chamber is well evacuated, the peaks are sharp and narrow; when gas is introduced, they become lower and broader, and sometimes they are visibly displaced. In certain cases (K^+ ions in helium, for instance) the height of the peak falls off exponentially with increase of pressure, and one deduces the value of σ by equation (9); it invariably turns out to be smaller than the value one gets by supposing both the ions and the atoms to have their gas-kinetic cross-sections, and decreases as the speed of the ions is increased. The data are thus in qualitive agreement with those of Ramsauer and Beeck, but a thoroughgoing comparison is yet to be made. The broadening of the peaks is a sign that the ions in their encounters with the particles of the gas are suffering small deflections with scarcely any loss of energy; the displacement of the peaks (when it occurs) a sign that they are losing small amounts of energy. A simple reduction in the height of a peak, unattended by broadening or displacement, might well indicate that the electron-transfers far outweigh the other modes of interception, and that the value of σ obtained is the σ for electron-transfer.

The value of σ for protons, Dempster found, is remarkably small. One may visualize these hydrogen nuclei as mere points, as one does an electron, and consider σ as the "cross-section for interception of protons" of molecules of the gas. Sending 900-volt protons through helium, in apparatus of the type above, Dempster observed the peak surviving even when the density of the gas was so great, that if σ had been equal to the gas-kinetic cross-section σ_0, more than half of the ions would have been intercepted in the first one-hundredth of their semi-circular path. It was considerably broadened, as though most of the protons had suffered small deflections; but at a density as much as one-seventh as great, there was hardly any broadening even;

[21] I must not give the impression that Dempster's scheme was a copy of Ramsauer's or Smyth's; it antedated both, having been used for other purposes, *e.g.* the detection of isotopes.

and at the high density, few had been deflected enough to be caught by the walls.[22]

G. P. Thomson developed another way of studying what happens to a stream of protons shooting through a gas. He set a photographic plate athwart the path of the narrow beam, and observed the imprint, which grew broader when a gas was introduced into the path. By measuring the darkening of the plate from point to point across the imprint, he was able to deduce the law of scattering-in-angle of the protons. The most interesting single feature of his data was a likeness to Ramsauer's famous observation with electrons: using either argon or helium, Thomson found that as the speed of the protons was decreased, the broadening of the beam rose to a maximum and then declined. This implies that for either gas the cross-section for interception of protons has a maximum, like that for interception of electrons. Moreover for either gas, the two cross-sections have their maxima at about the same *speed*, though not the same *kinetic energy*—owing to their difference in mass, a proton has some 1840 times as much vis viva as an electron keeping pace with it. Those with which Thomson was working had energy measured in thousands of volts.

Much of the work of Kallmann and Rosen is directed to testing the theorem stated above about the cross-section for electron-transfer. This they succeed in doing on a number of cases, with favorable results. Thus in nitrogen gas, the value of σ is much greater for N_2^+ ions than for N^+ ions; but in oxygen it is the N^+ ion for which the value of σ is greater, for the ionizing potential of the N atom lies closer to that of the O_2 molecule than does that of the N_2 molecule. Likewise Holzer has found that in hydrogen, the cross-section for interception is greater for H_2^+ than for either H^+ or H_3^+. It is not certain in any of these cases that the σ measured refers entirely to interception by electron-transfer, but the evidence nevertheless is strong.

The scattering of exceedingly fast helium nuclei—alpha-particles—is a subdivision of this field,—the best known, probably, of all, since out of it the central feature of our contemporary theory of the atom is derived. The value of σ for this scattering is vanishingly small, by comparison even with the gas-kinetic cross-section. But since the speed of the particles is so great, this result is for once exactly what we should expect.

[22] Dempster phrases the results in terms of the "mean free path," the reciprocal of $N\sigma$ (N standing for the number of atoms of gas per unit volume). The "high density" mentioned in this sentence was such, that the semi-circular path of the protons between the two slits was 108 times as long as the quantity $(N\sigma_0)^{-1}$ previously defined, the "gas-kinetic mean free path." Dempster also observed the extinction of a beam of H_2^+ ions, accompanied by the advent of a beam of slow-moving H^+ ions probably due to the dissociation of the former.

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