Some Contemporary Advances in Physics—II

By KARL K. DARROW

NOTE: Dr. Darrow, the author of the following article, has made it a practice to prepare abstracts and reviews of such recent researches in physics as appear to him to be of special interest. The results of Dr. Darrow's work have been available to the staffs of the Bell System laboratories for some time and having been very well regarded, it is thought that such a review, published from time to time in the TECHNICAL JOURNAL, might be welcomed by its readers.

The review cannot, of course, cover all the published results of physical research. The author chooses those articles which appear significant to him or instructive to his readers, without attempting to pass judgment on the scientific importance of the different papers published. It is not intended that the review shall always assume the same form; at one time it may cover many articles, at another be devoted to only a few, and it may occasionally treat of but a single piece of work.

The present installment, which is Number II, is devoted very largely to the subject of atomic structure.—EDITOR.

WE know quite definitely that an atom consists of a massive positively-charged nucleus with a certain number of electrons in its vicinity; but of the arrangement of these electrons in the strict geometrical sense we know very little—indeed, we do not certainly know even whether they are in motion or not. Apparently there are many possible arrangements for each kind of atom; one of these is a permanent arrangement, in the sense that when once established it is not changed so long as the atom is not disturbed from outside; the others are transient. In addition to the arrangements of the electrons in the neutral atom, there are the arrangements of the remaining electrons when one or more of the normal quota are lacking. When an atom changes over from one of these arrangements to another, it must take in or give out a definite quantity of energy. Another way of saying this same thing is that to each distinct arrangement of the electrons there corresponds a distinct value of the energy of the atom. These values of the energy of the atom are directly or indirectly measured, often with great precision; they are the data of experiment. The very precise statements, or at all events very definite statements, which are frequently made about the "structure" of the atom, usually refer only to these energy-values and the relations between them.

The simplest question that can be asked about the arrangement of the electrons is, whether they all occupy identical positions—being, for example, evenly distributed over the surface of a sphere or the circumference of a circle, with the nucleus at its centre. If this is true, the same amount of energy will be required to remove any

electron from the atom as to remove any other. In the extreme opposite case there would be as many different amounts of energy required to remove an electron from the atom as there were electrons. Now, when radiation of a definite frequency ν falls upon a group of atoms, any particular atom will either ignore the radiation, or else will absorb a definite quantity of energy $h\nu$ from it. (The letter h, as usual, denotes Planck's constant, $6.56 \cdot 10^{-27}$ ergs-seconds.) It

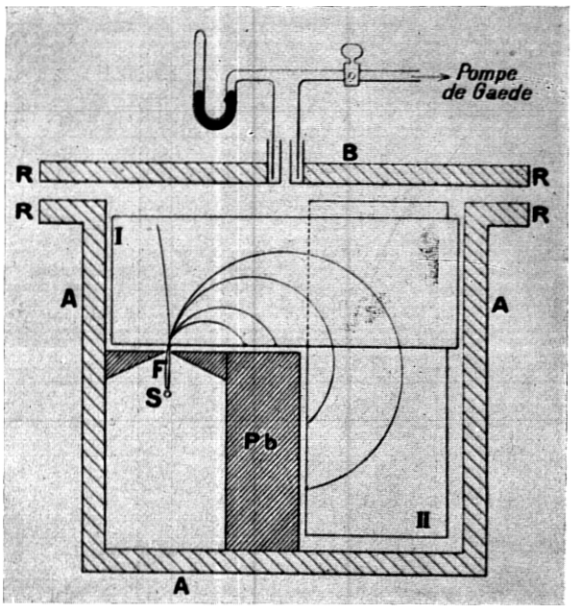

Fig. 1

follows that if an electron is extracted from an atom by this radiation and the work W required to extract it is not exactly as great as the amount $h\nu$, the difference will be turned over to the electron as kinetic energy, and the speed v with which it departs from the atom will be given by the equation

$$\frac{1}{2}mv^2 = h\nu - W$$

and W can be determined by measuring v. We can conveniently refer to W as an "extraction-energy" or "extraction-potential." If all the electrons occupy identical positions, W will be the same for all, and the emerging electrons will all have the same speed. If they occupy various positions or "levels" as is more commonly said, there

will be as many different electron-speeds represented in the emerging electron-stream as there are levels,[1] and from these speeds the extraction-energies characterizing (or indeed defining) the levels can be deduced.

The apparatus in which the test is made is of the type shown in Fig. 1. At *S* there is a long narrow rod or tube of the material being tested, irradiated by X-rays proceeding from a source at the left. A magnetic field, directed normally to the plane of the paper, sweeps

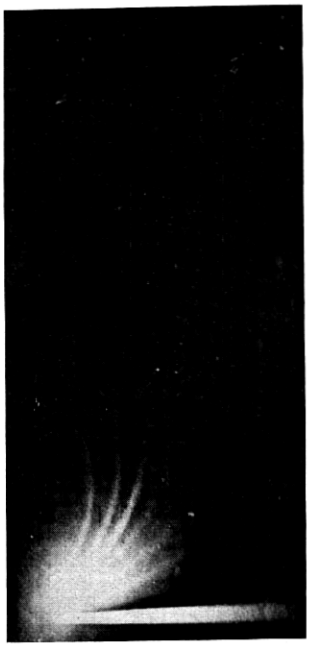

Fig. 2

the emerging electrons around in circular arcs, some of which pass through the slit; a few such arcs are sketched. The slower the electron, the more highly curved the path in which it travels; and the speed of the electron can be deduced from the curvature of the path. In Fig. 2 electron-paths of this type are reproduced from a photographic film, which was laid parallel to the plane of the paper, in the position of the rectangle marked I in Fig. 1. Fig. 3 shows arcs which appeared on a film laid in the position of the rectangle marked II.

[1] Of course there may be reasons why electrons in particular positions cannot often or at all be extracted by radiation, even though there is plenty of energy available.

These distinctly-separated arcs show that the emerging electrons fall into several distinct groups, each characterized by a particular speed. In Fig. 4 we see the traces of the electrons on films laid normally to

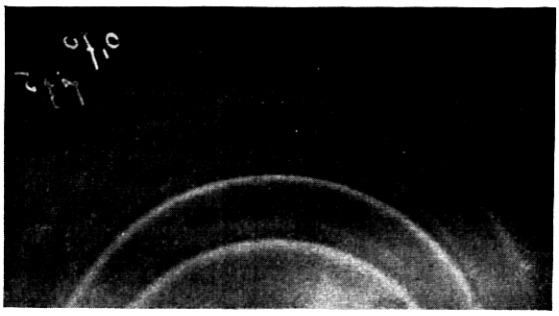

Fig. 3

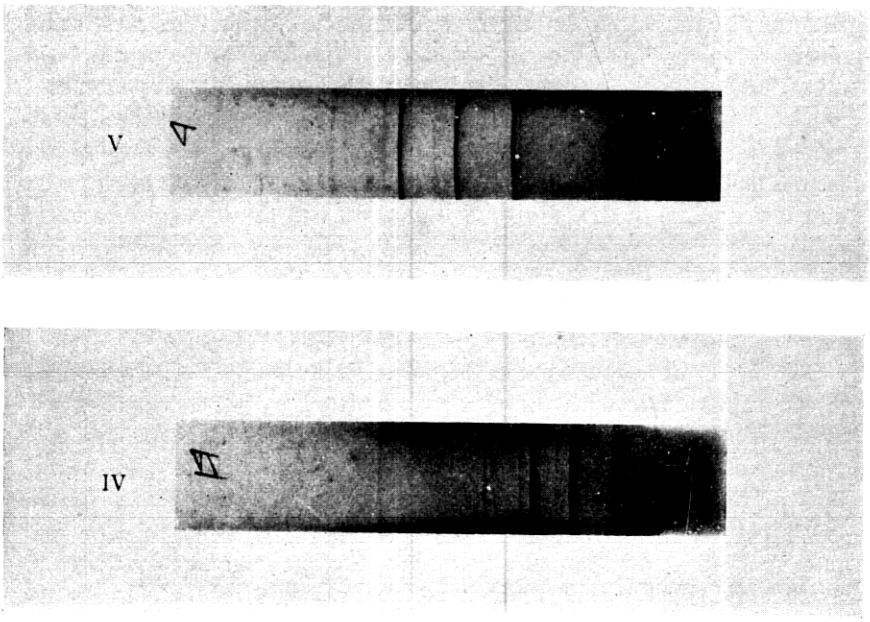

Fig. 4

the plane of the paper, along the top of the block marked "Pb" in Fig. 1. The appearance of the films at once suggests a line-spectrum. The lines, indeed, are the signatures of special electron-speeds instead of special radiation-frequencies; but these two quantities, being interconvertible, are not so profoundly different in their nature as

used to be supposed. Imitating de Broglie's term "spectres corpusculaires" we may call these "electronic spectra." But it must be remembered that they depend not only on the properties of the atom, but on the incident radiation as well.

Maurice de Broglie has undertaken an extensive study of these electronic spectra. His most recent apparatus, similar in general to the arrangement illustrated in Fig. 1 (with the photographic plate laid normally to the plane of the arcs) is improved in various respects and enlarged to permit of using a plate 24 cm. wide and electron-paths of 26.cm. radius. Unfortunately, the ideal condition of atoms irradiated by radiation of a single frequency, is unattainable. This is not merely because actual X-ray sources emit very mixed radiations intense at several distinct frequencies and perceptible at every frequency over a wide range. This difficulty could be partly remedied by appropriate filters. There is another difficulty and an inevitable one; the atoms from which electrons are extracted by the radiation promptly emit radiation of new frequencies, which extract other electrons themselves. In the language of the opening paragraph, the arrangement of electrons which results when an electron is extracted is not a permanent one; the remaining electrons redispose themselves in one arrangement after another, eventually arriving at the permanent one; to each successive arrangement corresponds a new and lower value of the energy of the atom, and the energy-differences ΔE are successively sent out in radiations of frequencies $\Delta E/h$. Thus there are several frequencies at work extracting electrons from the atoms; and in the electronic spectrum, each level is represented by as many lines as there are frequencies.

The uppermost spectrum of Fig. 5 is sketched by de Broglie from photographs made with the electrons emitted by silver atoms irradiated with the characteristic X-rays of tungsten.[2] The electron-speeds corresponding to the lines increase from left to right. There are four of these tungsten rays, two forming the $K\alpha$ doublet, while the other two, known as $K\beta$ and $K\delta$, have higher frequencies. The four lines marked 4 and 5 in the electronic spectrum are made by electrons extracted by these four radiations from a single level. This is the K-level, the deepest or innermost level in the silver atom, the electrons removed from it having lost more energy during the removal, than any others observed,—about $3.46 \cdot 10^{-8}$ ergs apiece. The two following doublets, marked 6 and 7, are made by electrons extracted by the $K\alpha$ frequencies from two distinct levels of the silver atom,

[2] Some photographs may be seen in the *Journal de Physique*, volume 2 of 1921. They were taken before the latest improvements were made in the apparatus, and do not show so much detail as the sketches; or perhaps the reproductions are imperfect.

known as the L and M levels respectively; the electrons from them have more energy left over after escaping. Line 8 is due to $K\beta$ extracting electrons from the L-level. The electrons ejected from the M-level by $K\beta$, and those ejected from the L and the M levels by $K\delta$, are presumably moving too rapidly to be received on the plate. At the other end of the spectrum the three lines 1, 2, 3 are due to electrons

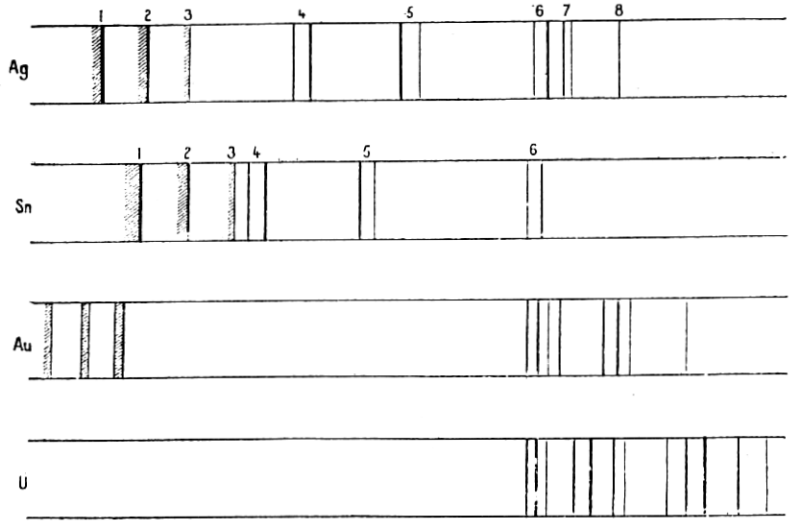

Fig. 5

expelled from the L and the M levels by two of the secondary X-ray frequencies proceeding from silver atoms: the $K\alpha$-doublet (not separated) and the $K\beta$-line of silver.[3] Just below this spectrum, we see the electronic spectrum of tin, in which the lines due to the primary X-rays from the tungsten are arranged like the corresponding lines in the silver spectrum, but displaced towards lower energies, since the levels in the tin atoms are different from those in the silver atom; while the lines due to the secondary X-rays are also repeated from the silver spectrum but with an opposite displacement, for in these cases both the levels from which the electrons are taken and the energies available for taking them out have been changed. Next come the spectra of gold and uranium. Each of these elements has more electrons per atom than the previous two (uranium has more

[3] From the nature of the rearrangements resulting in the $K\alpha$ and $K\beta$ radiations, it follows that the electrons extracted by the former from the M level have the same speeds (very nearly) as those excited by the latter from the L level; the two frequencies acting on the two levels produce three separable lines.

electrons, ninety-two, than any other element). The complexity of the spectra results from this richness of electrons, but the electrons extracted from the L and M levels of gold by its own radiations can be identified.

It is not necessary to provide an X-ray tube to supply the primary radiation; this can be supplied from the nuclei of radioactive atoms mingled with the atoms being tested, or, by examining radioactive substances, we can discover electronic spectra excited by radiations originating at the nuclei of the atoms themselves. Actually these were the earliest electronic spectra discovered; the first to be observed were photographed by von Baeyer, Hahn, and Meitner in 1910, years before the interpretation was made (the frequencies of the nuclear radiations were not then known). The figures 1, 2, 3 and 4, used to illustrate this article, are taken from a paper by J. Danysz, describing work performed in 1911 at the laboratory of Madame Curie in Paris, upon the electrons or beta-rays emerging from atoms of radium B and radium C. The grouping of these electrons, as we now know, results from their being extracted from the various levels by the several nuclear radiations and the inevitable secondary radiations which they produce in their own atoms. The large number of distinct groups (Rutherford and Robinson distinguished sixteen from radium B and forty-eight from radium C) is very likely due to several co-operating causes; there are several frequencies at work, the atoms have large numbers of electrons, and extractions probably occur exceptionally often where the radiations originate so close to the electrons. The earliest electronic spectra produced from non-radioactive atoms were excited by nuclear rays from radioactive substances, and the earliest rule discovered was that these spectra were very similar to the spectra of the radioactive atoms themselves; being indeed identical when the excited atoms are isotopes of the atoms which emit the exciting rays. In a complete account of this topic, many other names would be mentioned, notably those of C. D. Ellis and R. Whiddington.

A recently-published and relatively simple case is that of the radioactive atom, uranium X_1, of which the electronic spectrum is shown in Fig. 6 (from an article by Frl. Meitner). This displays three lines made by electrons of which the speeds indicate that they are extracted from the L, M and N levels of the atom by a single radiation, having itself the frequency of the natural $K\alpha$-radiation of the atom. This radiation was itself detected and identified by appropriate means. Faster electrons which were also observed, cannot have been derived from any such source; they probably came from

the nucleus, and some of them eject electrons from the K-level of the atom, thus producing the necessary condition for the $K\alpha$-radiation and all the others to be emitted. These electrons from the K-level would escape with too little energy to be registered in the apparatus. The question of the ultimate origin of these fastest electrons is, however, still under debate by the leading authorities on the subject.

Fig. 6

Imagine now that a beam of X-rays including all frequencies is directed against a thin sheet of metal atoms, and that the transmitted beam is dispersed into a spectrum projected against a photographic plate in the usual manner. Rays of frequency ν can extract electrons from a particular level when $h\nu$ exceeds the value of W for that level, but not otherwise. Advancing along the spectrum in the direction of increasing frequencies, we should expect to find a sudden sharp weakening of the transmitted rays wherever the frequency becomes equal to one of the values W/k which characterize the various levels. Some of L. de Broglie's classical photographs are shown in Fig. 7 (borrowed from Millikan's book, "The Electron"). The second picture from the top represents two spectra of an X-ray beam transmitted through molybdenum, one spectrum stretching away to the right from the central dark band, the other to the left. The frequency decreases as the distance from the dark band increases. Coming inwards toward the band, we see that the plate very suddenly becomes whiter at a certain critical frequency; this is the frequency at which $h\nu$ becomes equal to the W of the K-level. Similar spectra of beams transmitted through cadmium, antimony, barium and mercury are presented below the molybdenum spectrum; the corresponding absorption-edge is discerned in each, its frequency rising with the atomic number of the element.[4] This is by far the most delicate and accurate method of determining the various extraction-energies,

[4] The topmost picture shows the spectrum of the beam before it encounters the absorbing layer; the various strong lines in it, and the absorption-edges impressed upon it by the silver and bromine atoms in the photographic film, recur more or less clearly in the absorption-spectra, but have nothing to do with the atoms in the absorbing layer.

although by itself it merely shows that particular transformations of X-ray energy become possible at particular frequencies. The electronic spectra, although much less accurate for purposes of measurement, are needed to show how this absorbed X-ray energy is used.

These absorption-spectra show that the levels in the atom are much more numerous than the electronic spectra with their lower "resolving power" can reveal; for example, there are three L-levels and five

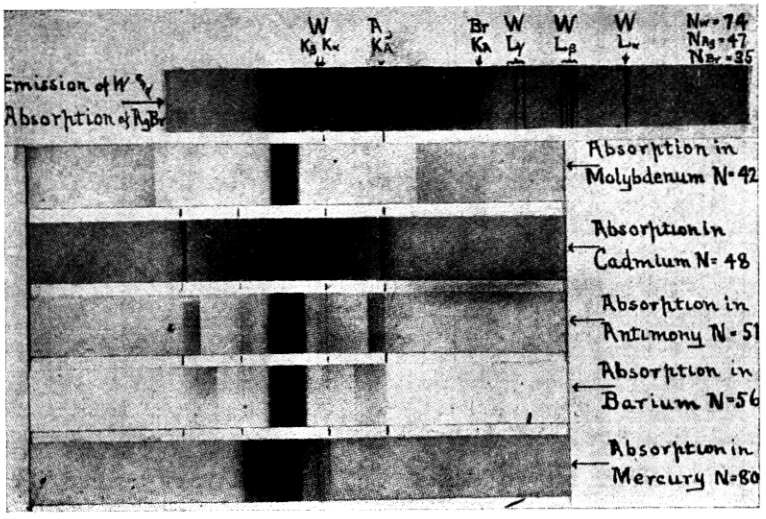

Fig. 7

M-levels. The five M-levels of thorium display themselves (not as clearly as might be desired) in Fig. 8, which consists of absorption-spectra photographed by P. A. Ross at Leland Stanford University. Each spectrum extends from low frequencies at the left to a maximum limiting-frequency at the right, the limit depending on the voltage applied to the X-ray tube and not on the properties of the absorbing atoms. As the limiting-frequency is increased by increasing the voltage, the absorption-edges resulting from electrons being extracted from the five M-levels successively appear. Along with each new absorption-edge there appear one or two new emission-lines, emitted by the thorium atoms during the rearrangements which follow upon the extraction of an electron.[5] These correspond

[5] Actually these lines were not emitted by the same atoms as absorbed the X-rays, but by thorium atoms in the target of the X-ray tube whence the primary X-rays came; the preliminary electron-extractions were performed in most cases by swift electrons. There is no reason to suppose that the agency effecting the electron-extraction has anything to do with the subsequent rearrangements of the atom.

to the secondary radiations of silver and tin, which we found to produce lines of their own in the electronic spectra of these elements. These relations between absorption-edges and emission-lines make

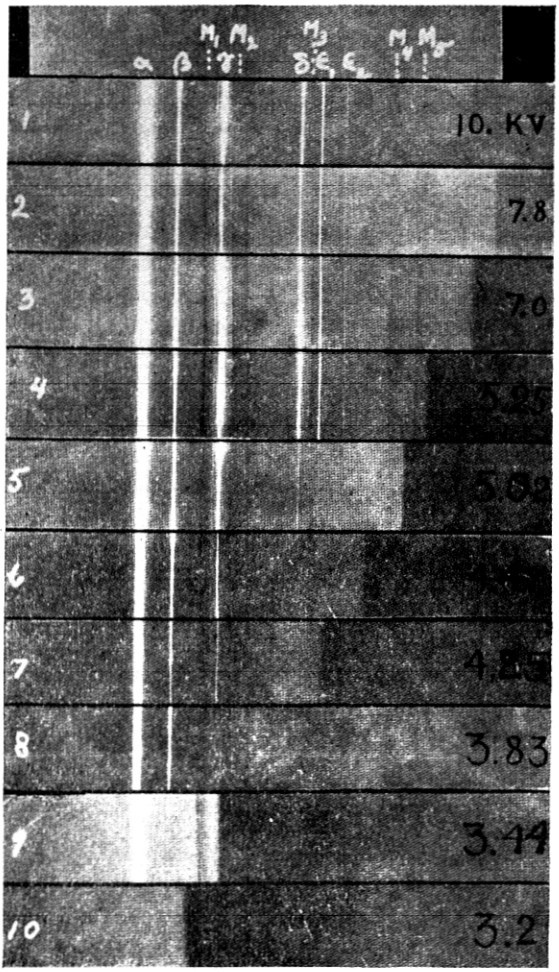

Fig. 8

it possible to use the X-ray emission-lines of atoms to identify and map out their levels.

This discussion of electronic spectra and X-ray absorptions has served to illustrate the remark made in the opening paragraph, that our knowledge about the various arrangements of the electrons

forming the atom consists mainly of data about their energy-values. We have a key to the arrangements themselves, and this is provided by the deflections of electrons as they pass through the atoms. An electron shot directly at an atom will be deflected by the combined actions of the nucleus and the atom-electrons; and by postulating a particular arrangement of the electrons we could, in principle at least, calculate the deflection. This may be likened to the performance of an astronomer who, observing a comet advancing into the solar system from outer space, calculates the path which it will follow through the system under the influence of the sun and the major planets, and the direction along which it will depart. The astronomer has the advantages of knowing exactly where the members of the solar system are, and of being able to follow individual comets. We do not know where the members of the electron-system are, and cannot shoot a single electron at an atom and discern its path.

The latter disadvantage is not as serious as it may seem. By projecting an enormous number of electrons in parallel directions against an atom or a layer of atoms, and measuring the fraction which are deviated through a given angle or range of angles, it is possible to test a particular atom-model. Assume that the atom possesses spherical symmetry; then the deflection suffered by an oncoming electron will depend only on a single variable, the minimum distance p from the centre of the atom to the line (extended) along which the electron approaches at first (before the deviation begins). Designating by ϕ the angle between the initial and final directions of motion of the electron (i.e., the amount of the deflection), we have

$$\phi = f(p) \qquad p = f^{-1}(\phi) \tag{1}$$

the function f depending on the particular atom-model. Suppose an enormous number N of electrons directed normally against a thin layer of metal atoms, in which Q atoms lie side by side. The number of electrons which will approach the layer along lines passing some atom-centre—any atom-centre—at distances greater than a given value p and less than a slightly greater given value $p+dp$, is

$$dN = NQ \cdot 2\pi p \cdot dp \tag{2}$$

This is likewise the number of electrons which will be deflected through angles lying between $\phi = f(p)$ and $\phi + d\phi = f(p+dp) = f(p) + (df/dp)dp$; which therefore may be written as

$$dN = NQ \cdot 2\pi p(dp/df)df = F(\phi)d\phi. \tag{4}$$

The expressions for p and dp/df are to be taken from equation (1). The function

$$F(\phi) = NQ \cdot 2\pi p(dp/d\phi) \tag{5}$$

represents the *distribution-in-angle* of the deflected electrons. If it is calculated for any particular atom-model and then determined by experiment, the comparison between calculation and data affords a test of the atom-model. An instructive comparison can be made even if the value of NQ is unknown, since the form of the *F-versus-ϕ* curve, as well as the absolute height of its ordinates, depends upon the atom-model.

For electrons or other charged particles of charge e and mass m, streaming with uniform speed U against a group of much more massive nuclei each bearing a charge E, the functions f and F assume the forms

$$f(p) = 2 \cdot \text{arc cot } (mU^2p/eE) \tag{6}$$

$$F(\phi) = NQ\pi(eE/mU^2)^2 \cot (\tfrac{1}{2}\phi) \operatorname{cosec}^2(\tfrac{1}{2}\phi). \tag{7}$$

This case, insignificant as it may appear, suddenly assumed the greatest importance when, in 1913, Rutherford, Geiger and Marsden established that the distribution-in-angle of alpha-particles (particles of twice the charge and about 7,500 times the mass of an electron) deflected by metal atoms is of precisely the form (7). This means that around each atom-nucleus there is an empty space so wide that full-speed alpha-particles passing close enough to a nucleus to be deflected through 5° or more, undergo almost their entire deflection within it; hence, most or all of the electrons surrounding the nucleus must lie beyond this vacant central region. From the data of these classical experiments, Rutherford and his collaborators deduced that the radius of the empty region encircling the gold nucleus is at least 36×10^{-12} cm. After the war, the problem was again taken up in Rutherford's laboratory in Cambridge. J. Chadwick gave 14×10^{-12} cm. as a minimum value for the radius of the vacant space around the platinum nucleus. Last year P. M. S. Blackett made a statistical study of the deflections of comparatively slow alpha-particles, using the C. T. R. Wilson expansion-method, which was described in the last issue of this Journal. Paths of some of these deflected particles are shown in Fig. 9. By using these slow-moving particles, which begin to turn in their courses while still much farther away from the nucleus than the minimum distance at which fast alpha-particles begin to respond to its repulsion, Blackett was able to search farther

out for the outer boundary of the empty space. The deflecting atoms were atoms of argon, each consisting of eighteen electrons surrounding a nucleus; atoms of oxygen with eight electrons apiece, and atoms of nitrogen with seven (the latter two kinds of atoms not being discriminated in the study of the data). Blackett concluded that the

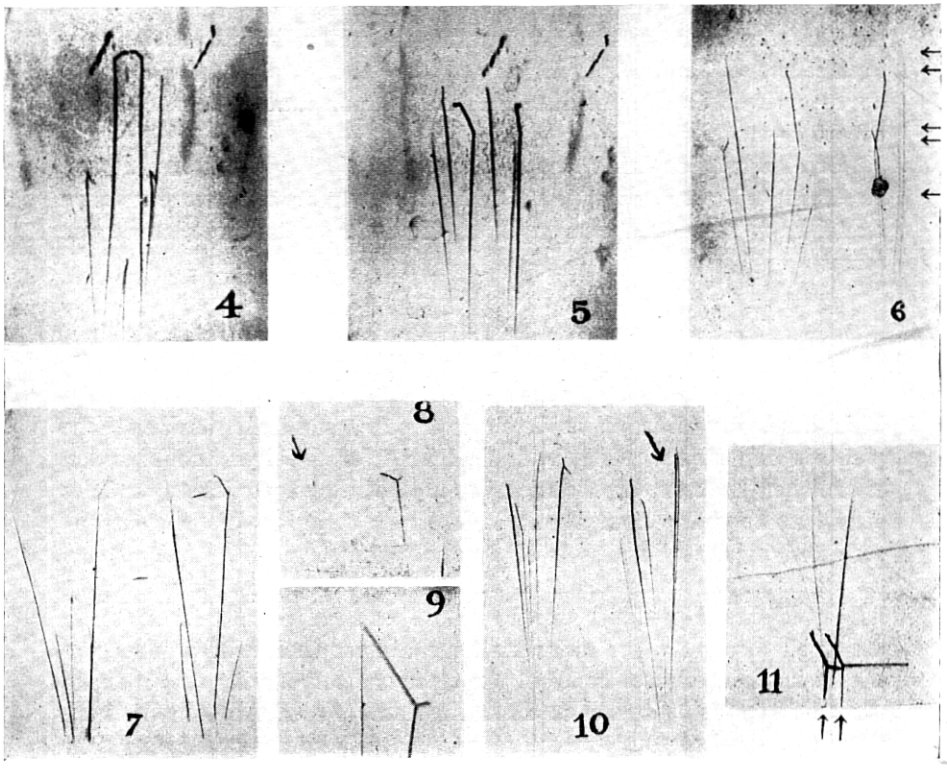

Fig. 9

empty space in the argon atom extends out at least to a distance of 10^{-9} cm. from the nucleus in the argon atom, and to a distance of at least 5×10^{-10} cm. in the nitrogen and oxygen atoms.

We now pass to the case of electrons deflected by atoms. Since the electron is so very much lighter than the alpha-particle, and yet is half as strongly charged, it will be much more seriously deflected by a nucleus than an alpha-particle, approaching along the same line with the same speed, would be. This contrast is very strikingly illustrated by two results published last summer. Harkins and Ryan, photographing the paths of eighty thousand alpha-particles

through air, found only three instances of deflections exceeding 90°; C. T. R. Wilson, photographing the paths of 503 fast electrons through air, found forty-four instances of deflections exceeding 90°. While, in general, it would be hardly fair to make such comparisons without allowing for the relative energies of the two kinds of particles, the difference in order of magnitude is so great that we may accept it as typical.

Moreover, the electron will be deflected by the atom-electrons as well as by the nucleus, and will not disarrange the atom-electrons so badly on its way through the atom-system. These deflections

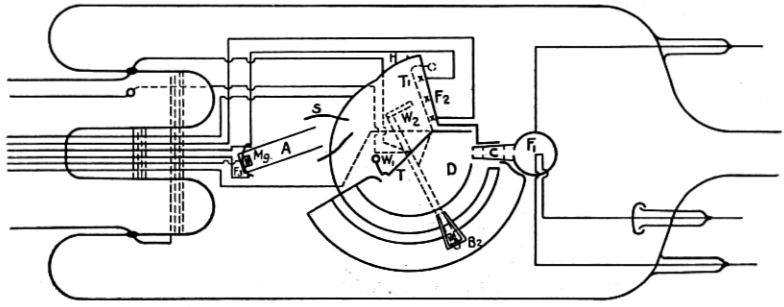

Fig. 10

will be superposed upon the deflection produced by the nucleus, and will modify the distribution-in-angle function F from form (7) into some other form. Such modifications have been suspected by several investigators; for example, by Crowther and Schonland in their study of the deflections of very fast electrons by metal atoms. It has been argued by Wentzel, however, that the distribution-in-angle function observed in their experiments departed from the form (7) not because the atom-electrons were interfering with the fast electrons, but because some of the deflected electrons had been deviated by several atom-nuclei in succession.

C. Davisson and C. H. Kunsman, in the laboratories of the Western Electric Company, made the first definite attempt to produce electron-deflections under conditions in which the distribution-in-angle function would disclose the influence of the atom-electrons. To do this it was desirable to use, not the fast electrons from radioactive atoms which previous experimenters had employed, but slow electrons of controllable speed. A diagram of their apparatus is shown in Fig. 10 and a photograph in Fig. 11. The electrons proceed from a hot filament at F_1, strike the metal target at T, and are deflected through various angles; the shielded collector B_1, swinging from one angle to

another, successively receives the electrons deflected through the various angles. The electrons depart from F_1 with very low speeds and receive the speed U through acceleration by a voltage applied between F_1 and the cylinder surrounding F_1; thereafter they move with constant speed in an equipotential region, through the various

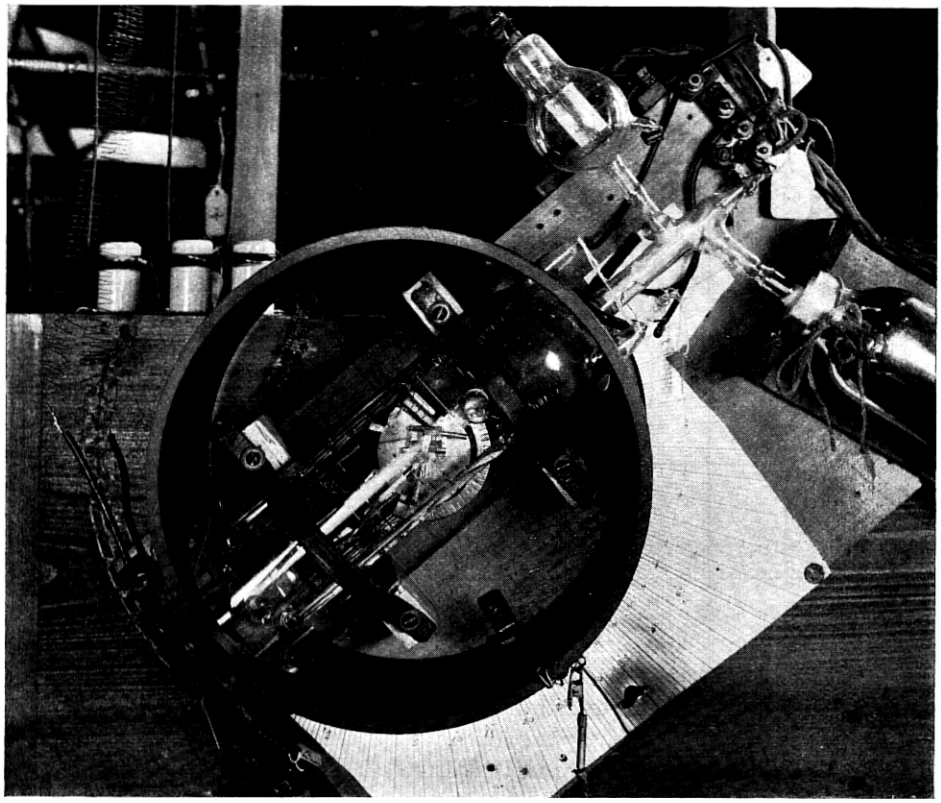

Fig. 11

slits shown in the diagram around C, and against the target. Among the electrons which emerge from the target, there are some which have been deflected by individual atoms in the way we have been describing, but very many more which have either undergone several deflections in succession or else were not in the incident beam but have been dislodged from their places in the target metal by the primary electrons. If these latter were allowed to reach the collector, the distribution-in-angle function of the once-deflected electrons would be blurred and concealed by the unwanted electrons. As,

however, they have not so much energy as the primary or the once-deflected electrons, they can be kept away from the collector by lowering its potential to a value such that only such electrons as have, say, 90% of the energy of the primary electrons can reach it. Thus the filament may be at potential zero, the target at 500 volts; if the collector is also at 500 volts, the distribution-in-angle function of the

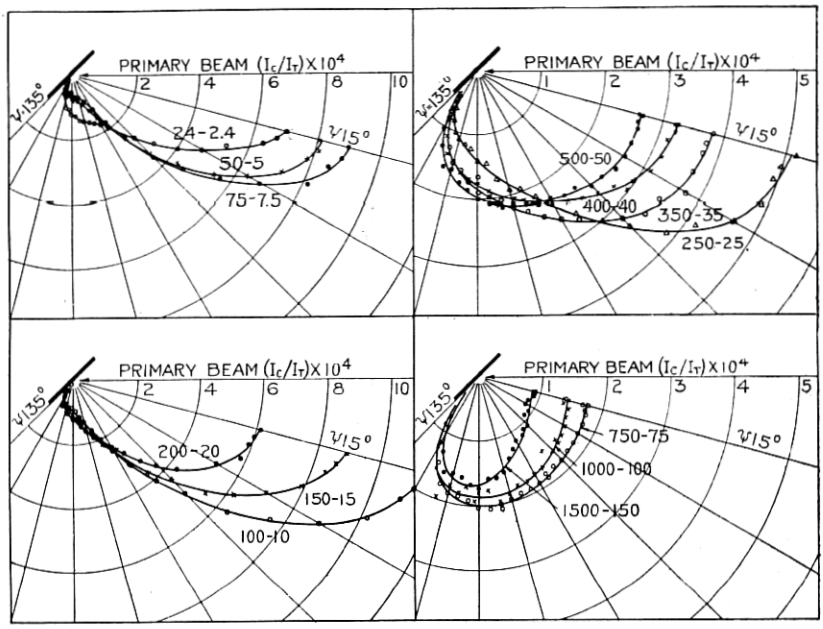

Fig. 12

electrons it receives has nothing in common with the function F characterizing the once-deflected electrons; but when the collector is lowered to 50 volts, the distribution-in-angle function which it records assumes a new and characteristic form.

Some of these angular distributions are shown in Fig. 12 (for magnesium) and Fig. 13 (for platinum). The latter curves were obtained first, with a platinum target; then the target was overlaid with a thin film of magnesium, formed by sublimation without opening or altering the tube, and the sharply-contrasted curves of Fig. 12 replaced the others. The distribution-in-angle of the engineering electrons is plotted, naturally, in polar coordinates; the direction $\phi = 0°$, i.e., the direction of motion of the primary electrons, is indi-

cated by the arrow and the lettering. Such a symbol as "100–10" indicates that the corresponding curve was taken down with the target at 100 volts and the collector at 10 volts (the filament always being at zero potential). The reason for this has been explained above; the family of curves in Fig. 12 illustrates the point.

These are examples of the curves from which the arrangement of the atom-electrons is to be inferred. The sinuous and serrated curves for platinum, entirely different from the smoothly rounded curves

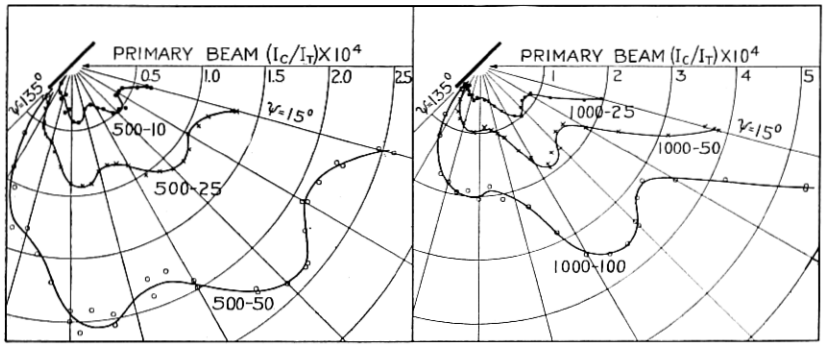

Fig. 13

derived from equation (7), surely owe their shape to the numerous levels among which, as was shown in the foregoing pages, the electrons of massive and electron-rich atoms are distributed; the platinum atom, with its seventy-eight electrons, ranks among the most complicated of all. The magnesium atoms, with their thirteen electrons apiece, are simpler and yield curves which are simpler, but not of the type of equation (7).

To interpret these curves Davisson has calculated the distribution-in-angle function for electrons deflected by an idealized "limited-field" atom-model, in which there is a concentrated charge $+E$ at the centre and a charge $-E$ uniformly spread over a spherical surface of radius R. This uniformly-charged sphere is a sort of first-approximation substitute for a spherical surface on which several electrons are arranged. It is not implied that the magnesium atom has all its electrons at the same distance from the nucleus, which would be most improbable, as its X-ray spectrum shows at least two distinct levels; we can suppose that n out of the 12 electrons are so close to the nucleus that together with it, they practically

form a single point-charge $(12-n)e$, and the remaining $(12-n)$ electrons lie on the spherical surface, which encloses the "empty space" mentioned above. The functions f and F assume the forms

$$f(p) = 2 \text{ arc } \cot \frac{p(2\mu-1)}{\sqrt{R^2-p^2}} \tag{6a}$$

$$F(\varphi) = NQ\pi \cot(\tfrac{1}{2}\phi) \operatorname{cosec}^2(\tfrac{1}{2}\phi) \frac{(2\mu-1)^2R^2}{[\cot^2(\tfrac{1}{2}\phi)+(2\mu-1)^2]^2}, \tag{7a}$$

in which $\mu = \frac{1}{2}mU^2R/eE$; the symbols have the same meanings as in (6), and (7), with which these equations become identical if R is made infinite.

This "limited-field" distribution-function has some odd characteristics. At very high speeds large deflections naturally are rare, but as the speed is lowered they become relatively more frequent; the 1,500-volt, 1,000-volt and 750-volt curves for magnesium illustrate this. This tendency gains rapidly as U is decreased; at a certain critical value, given by $\mu = 1$, the deflections are uniformly distributed in all directions [6]; at a lower critical value, given by $\mu = \frac{1}{2}$, all the electrons are turned through 180° and return on their tracks. As the speed is still further decreased, the condition of uniformly-distributed deflections is again approached, and we have the extraordinary feature of the average deflection decreasing as the energy of the electrons goes down.[7] In the family of curves for magnesium there appears very clearly an intermediate velocity at which 180° deflections are peculiarly frequent; the curves spread outward in the direction $\phi = 180°$ whence the primary electrons come, as the energy of the primaries rises from 24 to 75 volts, and retract themselves again as the energy rises beyond 100 volts. This is a particularly important feature of the curves.

To make an adequate test of the new expression for F, it is necessary to apply certain corrections to the curves presented, particularly a correction required because the distance travelled by the deflected electrons within the target metal varies with ϕ, so that the percentage which goes astray, owing to loss of speed or otherwise, varies similarly. A curve exempt from this correction can, however, be ob-

[6] Meaning that the number deflected per unit solid angle is independent of ϕ, which means that the distribution-in-angle function is of the form *const.* $(\sin \phi)$.

[7] It may be recalled from the last number of this Journal, page 110, that H. A. Wilson used this property as an explanation of the anomalous variations of electron-mean-free-paths with speed in various gases.

tained in a certain manner.[8] On studying this curve, it is found that the critical speed at which 180° deflections are most frequent is too low. This indicates that an incident electron approaching an atom is accelerated toward it, by virtue of the total charge of the electrons on the spherical shell not quite compensating the nuclear charge; the speed U which figures in the equations is therefore greater than the measured speed with which the electrons are fired at the target. (This interpretation also serves to explain the lobe observed on the lowest-speed curves for magnesium, and suggests the reason for the lobes of the curves for platinum.)

The curves are satisfactorily explained, if we build the magnesium atom in this manner: a nucleus of charge $12e$, two electrons so near it that the central charge is effectually $10e$, and a spherical shell of six electrons with a radius of $1.28 \cdot 10^{-9}$ cm.; the other four electrons much further out, perhaps dispersed and wandering through the metal. The only arbitrary assumption made is that about the two deep-seated electrons; the radius R of the shell and the number of electrons upon it are prescribed by the curves, once that assumption is made. If we assume three deep-seated electrons, R becomes $1.15 \cdot 10^{-9}$ cm. and the number of electrons in the shell drops to five. The shell must be the L-level, and the deep-seated electrons constitute the K-level.[9]

The energy required to remove the loosest or outermost electrons of the atom is generally determined, as is well enough known, by smiting the atom with an electron instead of with one of the radiation quanta used in extracting the inner electrons.[10] Usually the quantity measured is simply the energy which the striking electron must have, in order to convert the atom or molecule into a positively-charged ion; the negative charge removed from the atom is assumed without proof to be a single electron. On the other hand, J. J. Thomson

[8] Imagine an electron incident at angle θ on the target surface, and deflected through angle ϕ (in the plane of incidence) by an atom which it meets after penetrating a distance d in a straight line. If it continues in a straight line from the point of deflection until it emerges, it travels a distance $x = d\,(1+\cos\theta \cdot \sec(\psi-\theta))$, where $\psi = \pi - \theta$. This distance x will be the same for any two values ψ_1 and ψ_2 of ψ, such that $\psi_1 + \psi_2 = 2\theta$. Insofar as the number of deflected electrons emerging with speed sufficient to reach the collector depends on x, it will be the same for both values of ψ. The curve representing the ratio of the number of electrons reaching the collector, for two such angles, plotted versus U, is exempt from this correction, and can be directly compared with a theoretical curve.

[9] Or we could assume that there were no deep-seated electrons, and give seven electrons and a radius $1.54 \cdot 10^{-9}$ cm. to the shell; but then we should have nothing to serve as a K-level.

[10] Generally the frequency required to extract the outermost electron with a quantum lies in the most inconvenient region of the spectrum for practical work.

and many others have measured the charges [11] of ionized atoms in discharge-tubes, and found them sometimes single and sometimes multiple electron-charges, but have not measured the minimum energy required to produce a particular kind of ionization. H. D. Smyth, at Princeton and Cavendish, was the first to combine both methods; he ionized atoms by electron-impacts in a tube designed for determining ionization-potentials in the accepted manner, and after further accelerating the ions drew them through a channel into a second tube where they were deflected in a magnetic field so that their charges could be measured. The difficulty to be surmounted is that in the first tube the pressure of the gas must be high enough to yield a satisfactory number of ions, and in the second tube it must be low enough not to interfere with the arcs described by the ions in the magnetic field. At first he sent a beam of mercury vapor rushing transversely across his first tube from a boiler into a liquid-air trap; by first sending the atoms down a long tube with a system of diaphragms and so stopping the obliquely-moving ones, he was able to prevent atoms from straying out of the beam in the critical zone. Later he attacked a more difficult case, that of nitrogen; the gas was continuously fed into the first tube and a powerful pump drew it out before it could diffuse seriously into the second tube.

While it is interesting to have direct confirmation that the first and easiest ionization is the extraction of a single electron, Smyth's most important results refer to the later ionizations. Mercury atoms that had lost two electrons appeared in the second tube when the bombarding potential attained 19 volts, nine volts more than the first ionizing-potential; at a much higher voltage, triply-charged atoms were detected, or at least suspected. In nitrogen, the earliest ionization, at about 16 volts, does not involve dissociation, but at a potential 8 volts higher, a doubly-ionized single nitrogen atom makes its appearance, and a little further along, Smyth detects an ion which may be a singly-ionized nitrogen atom or a doubly ionized molecule (the two possibilities cannot be discriminated by this method, but the second seems improbable). Valuable knowledge about the relations between ionization and dissociation—between, that is, the removal of an electron from a molecule, and the breaking of the bonds that hold the atoms of the molecule together—may be expected from experiments of this type.

Something more is to be said on two of the topics of the last article in this series. A. H. Compton's discovery that scattered X-rays consist of two distinct radiations, one with the frequency of the

[11] Actually, the charge-mass ratios.

primary rays and the other with a slightly lower frequency, was mentioned in that article; he has since published an account of a series of measurements made, not on the wave-length but on the absorption-coefficient (in various substances) of the scattered rays, and finds it altered from that of the primary rays in the sense and more or less in the magnitude to be expected from the wave-length measurements of the lower-frequency rays. The largest alterations and the best agreements with theory are obtained with light atoms and high-frequency rays. In the frequency-range of the visible spectrum, the scattered ray of lowered frequency, sought for by P. A. Ross in light of the wave-length 5461A scattered by mercury vapor, is altogether lacking. The transparency of krypton and xenon atoms to slow electrons, discovered by Minkowski and Sponer, has been confirmed by Ramsauer with his original (and better) method. The transparency of argon atoms has also been verified by O. W. Richardson and R. N. Chaudhuri, by a method sufficiently different from the others to rank as an independent test.

REFERENCES

O. von Baeyer, O. Hahn, and L. Meitner: Phys. ZS, *11*, pp. 488-493 (1910); *12*, pp. 273-279 (1911).
P. M. S. Blackett: Proc. Roy. Soc. *102A*, pp. 1-17 (1922).
L. de Broglie: Jour. de Phys. (5) *6*, pp. 161-168 (1916).
M. de Broglie: Jour. de Phys. (6) *2*, pp. 265-267 (1921); C. R. *173*, *172* (1922).
J. Chadwick: Phil. Mag. *40*, pp. 734-746 (1920).
A. H. Compton: Phil. Mag. *46*, pp. 897-911 (1923).
J. Danysz: Le Radium *9*, pp. 1-6 (1912); *10*, pp. 4-6 (1913).
C. Davisson, C. H. Kunsman: Science, November 25, 1921 and later issues; Phys. Rev. *21*, pp. 637-649 (1923); Phys. Rev. *22*, pp. 242-258 (1923).
C. D. Ellis: Proc. Roy. Soc. *101A*, pp. 1-17 (1922).
H. Geiger and E. Marsden: Phil. Mag. *25*, pp. 604-623 (1913).
W. D. Harkins and R. D. Ryan: Jour. Am. Chem. Soc. *45*, pp. 2095-2107 (1923).
L. Meitner: ZS. f. Phys. *17*, pp. 54-66 (1923).
C. Ramsauer: Ann. d. Phys. *72*, pp. 345-352 (1923).
O. W. Richardson, R. N. Chaudhuri: Phil. Mag. *45*, pp. 337-352, and *46*, pp. 461-472, 553-564 (1923).
P. A. Ross: Phys. Rev. *22*, pp. 201-202 (1923). (Scattering of light.)
P. A. Ross: Phys. Rev. *22*, pp. 221-225 (1923). (X-ray spectra.)
E. Rutherford: Phil. Mag. *21*, pp. 669-688 (1911). (Deflection of charged particles by atom-nuclei.)
E. Rutherford and H. Robinson: Phil. Mag. *26*, pp. 717-729 (1913).
H. D. Smyth: Proc. Roy. Soc. *102A*, pp. 283-293 (1922-23); *104A*, pp. 121-134 (1923).
G. Wentzel: Phys. ZS, *23*, pp. 435-436 (1922). Ann. d. Phys. *69* (1922).
R. Whiddington: Phil. Mag. *43*, pp. 1116-1126 (1922).
C. T. R. Wilson: Proc. Roy. Soc. *104A*, pp. 192-212; 1923.