A CONTRIBUTION TO THE THEORY OF IONIZATION CHAMBER MEASUREMENTS AT LOW PRESSURES

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THE ionization chamber theory of Bragg (1912), Fricke and Glasser (1925), and Gray (1928) is of such fundamental importance in the measurement of ionizing radiations that it has been tested experimentally by various investigators. A summary of the results of these experiments was given by Sievert (1940), who included some measurements of his own. The points usually investigated have been the variation of ionization with chamber volume and with the pressure of the filling gas, theory predicting direct proportionality in both cases. Although some workers have found such proportionality to hold within experimental error over the ranges they have investigated, others have observed deviations from proportionality. With very few exceptions these deviations have been in the direction of an excess of measured current as the volume or pressure was decreased.

In this paper it is suggested that this excess is not due to an excess of ionization over that predicted by theory, but is due to the effect of the voltage applied to the ionization chamber on the electron exchange between the electrodes of the chamber.

MEASUREMENTS AT SENSIBLY ZERO PRESSURE

Consider first experiments at sensibly zero pressure, where ionization must play a negligible part. Taylor (1951) gives some results showing that a reduction of pressure to about 10^{-9} atmospheres only reduced the measured current to 10^{-4} of that at atmospheric pressure, the measured current therefore being 10^5 times that to be expected on ionization chamber theory. Wilson (this Journal, p. 158) also observes an appreciable current at zero pressure.

The most obvious cause is a natural leak or drift in the apparatus, but this is normally allowed for. Nevertheless the residual current may be a radiation-induced leak (Farmer, 1945) in the insulator of the ionization chamber. This is most difficult to allow for as the leakage decreases when irradiation stops. This leakage might also account for the gross asymmetry of the voltage-current curve observed at low pressures. Farmer (private communication) has found that the radiation-induced leakage of polyethylene insulated coaxial cable frequently varies with the direction as well as the magnitude of the electric field across the insulator.

Although radiation-induced leakage may contribute to the measured current at zero pressure, it cannot be the sole contributing factor. Taylor's finding that under similar conditions the current in a brass chamber was ten times that in a bakelite one for radiation produced at 100 kV and filtered by 1 mm Cu indicates that the material of the chamber is of much greater importance. The variation of the current at zero pressure with the wavelength of the radiation falling on the chamber points strongly to electron emission from the walls of the chamber being responsible for the currents observed.

EFFECT OF CHAMBER VOLTAGE ON ELECTRON EXCHANGE BETWEEN ELECTRODES

In general in an ionization chamber exposed to ionizing radiation, there will be a net electron transfer from one electrode to the other. This may be due to a difference in the materials of the electrodes, a non-uniform dose-rate throughout the chamber, or some asymmetry in the electron emission. It is usually supposed that in cases where electron transfer may be appreciable, *e.g.* electron dosimetry and some γ-ray measurements (Failla and Marinelli, 1937), taking the mean of the currents obtained with alternately positive and negative volts on the collecting electrode eliminates electron transfer from the measured current. This is not quite true, and when electron transfer is all important, *i.e.* at zero pressure, the error involved is considerable.

(*a*) *Infinite plane parallel electrodes*

Consider first infinite plane parallel electrodes placed one above the other with a vacuum between. Suppose the electron flow to or from the lower electrode is being measured. When the lower electrode is positive with respect to the upper electrode all electrons emitted downwards from the upper electrode will reach the lower electrode. All electrons emitted upwards from the lower electrode will escape from it, *except those which have a kinetic energy (expressed in eV), associated with the component of the velocity perpendicular to the electrodes, which is less than the voltage between the electrodes.* The electron flow to the lower electrode will therefore be greater than it was in the absence of the voltage

across the chamber. When the lower electrode is negative with respect to the upper electrode, its net electron emission is measured. All electrons emitted by it will escape, and all those emitted from the upper electrode towards the lower electrode will reach it, *except those having kinetic energy, associated with the component of the velocity perpendicular to the plates, less than the applied chamber voltage.* The net electron emission will therefore be greater than that in the absence of the chamber voltage. Thus the application of a voltage to the chamber is seen in both cases to increase the current it was intended to measure, and the electron transfer is not eliminated by taking the mean of the two measured currents. If the electron emission is isotropic and both electrodes are exposed to the same intensity of radiation, the current-voltage curve should be symmetrical about the voltage zero.

(*b*) *Concentric spherical electrodes*

Consider next the electron transfer between concentric spherical electrodes *in vacuo*. Any electron emitted from the outer wall will travel initially parallel to some diameter such as AB (Fig. 1) at a

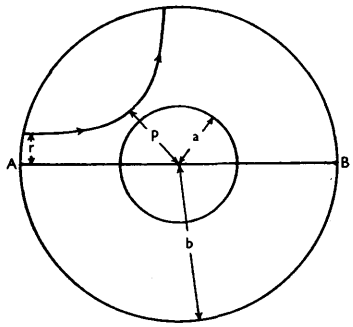

FIG. 1.

distance r, say, from it. Suppose the central electrode is negatively charged, the closest distance of approach of the electron to the centre of the chamber is p and the electron's emission energy is E electron volts. Let V be the voltage between the chamber electrodes. Consider the limiting case in which the electron just touches the central electrode, *i.e.* p=a. From the conservation of energy, the kinetic energy of the electron will be $(E-V)$ electron volts at the central electrode, the potential energy having increased by V electron volts. From the conservation of angular momentum, $r\sqrt{E}=a\sqrt{E-V}$. Thus $r=a\sqrt{1-V/E}$, and $(a^2-r^2)/a^2=V/E$.

Of the electrons emitted towards the central electrode a fraction $(a^2-r^2)/a^2$ are deflected from it. Therefore, the fraction deflected$=V/E$. If N=the number of electrons emitted per cm.^{2} of electrode, the number emitted towards the central electrode $=4\pi a^2N$. The number deflected is therefore $4\pi a^2NV/E$. When the central electrode is negative any electrons emitted by it will escape. Therefore if the net electron emission of this electrode is measured, it will be too great by $4\pi a^2NV/E$. This expression is only true, of course, if V is not greater than E.

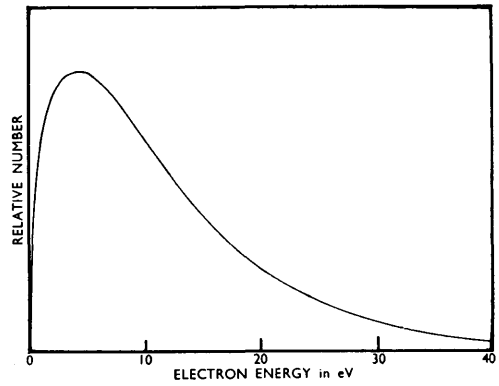

FIG. 2.

Approximate energy distribution of low energy electrons emerging from walls of ionization chamber.

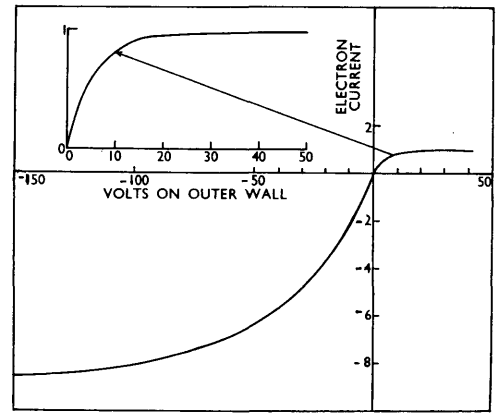

FIG. 3.

Calculated saturation curve for a spherical chamber with outer wall radius 3 × inner electrode radius. Electron energy distribution as in Fig. 2.

If the central electrode is positive similar arguments show that the number of electrons drawn into the central electrode (*i.e.* the number in excess of those emitted towards the central electrode) is again $4\pi a^2NV/E$, but in this case the expression is valid for values of V/E not exceeding $(b^2/a^2)-1$, namely, that value of V/E at which all electrons emitted from the outer wall reach the central electrode.

Similarly it may be shown that the number of electrons emitted by a positive central electrode which returns to that electrode is $4\pi N[a^2-b^2(1-V/E)]$, which expression is valid for $1>V/E>1-a^2/b^2$. If $V/E>1$ all electrons (*i.e.* $4\pi Na^2$) return, while if $V/E<1-a^2/b^2$ all electrons escape.

From these expressions it may be seen that the excess current measured when the central electrode is positive is never less than that measured when the central electrode is negative, and, in fact, the former may considerably exceed the latter when $V>E$, particularly when the radius of the outer wall is much greater than that of the central electrode. There will therefore be considerable asymmetry in the voltage-current characteristics of the chamber (see Fig. 3).

Because of the spherical symmetry of the chamber the above expressions should be valid even if the electron emission is not isotropic.

(*c*) *Coaxial cylindrical electrodes*

Using the same nomenclature and the same argument as for spherical electrodes it may be shown that for cylindrical electrodes the minimum value of r (Fig. 1) for which electrons will just be deflected from a negative central electrode is given by $r=a\sqrt{1-V/E}$, but here E is the energy of emission associated with the component of velocity in a plane perpendicular to the axis of the cylindrical electrodes.

Of the electrons emitted towards the central electrode a fraction $(a-r)/a$ are deflected from it, *i.e.* fraction deflected $=1-\sqrt{1-V/E}$. The number deflected per cm length of cylindrical electrode is therefore $2\pi aN(1-\sqrt{1-V/E})$, where N is the number of electrons emitted per cm^2 with energy E associated with the component of velocity in a plane perpendicular to the cylinder axis. This expression is only valid for values of V not greater than E, *i.e.* the maximum number that can be deflected is $2\pi aN$.

It may be shown that when the central electrode is positive the number of electrons deflected into it is $2\pi aN(\sqrt{1+V/E}-1)$. This expression holds for values of V/E up to $(b^2/a^2)-1$, at which value all the electrons emitted from the outer wall, and which in the absence of any chamber volts would miss the central electrode, are deflected into it. Also the number of electrons emitted from a positive central electrode which is attracted back into that electrode is $2\pi N(a-b\sqrt{1-V/E})$ for $1>V/E>1-a^2/b^2$. If $V/E>1$ all the $2\pi Na$ electrons are attracted back, whereas if $V/E<1-a^2/b^2$ they all escape.

All these expressions will only lead to a true value of the net electron transfer from one electrode to the other if reflections are negligible. The proportion of slow electrons reflected can be as high as 0·3, but is usually very much less.

Energy Distribution of Electrons in an Irradiated Material

The expressions derived for the numbers of electrons deflected into or away from the measuring electrode all involve the ratio V/E. The effect of a chamber voltage of about 100 volts will therefore be small unless many of the electrons emitted from the chamber wall have energies less than 100 electron volts. Cormack and Johns (1952) have calculated both the initial energy distribution of the primary electrons released in water by a variety of high-energy radiations, and the energy distribution of the primary electrons crossing a plane within the irradiated water. The numbers of these electrons which would be deflected under the conditions used by Wilson and Taylor are too small by some orders of magnitude to account for the currents which they obtained.

However, a primary electron released in water by 200 kV X rays or by radium γ rays produces approximately 10^3 or 10^4 ion pairs respectively. Since each ion pair may be supposed to involve the existence of a free electron (at least temporarily), these electrons might be sufficient to account for the currents observed providing their energies are sufficiently small.

The theoretical derivation of the exact energy distribution of these electrons would not seem to be possible at present, but some approximations may be made and some experimental evidence is available. Calculations tabulated by Lea (1946, pages 25 and 28) indicate that for primary electrons of energies between 0·5 and 380 keV primary ions are about 20 times as numerous as δ rays of energy greater than 100 eV. Thus of all the electrons *liberated* by primary electrons in tissue, about 5 per cent have energies in excess of 100 eV; but these secondary electrons produce tertiary electrons the numbers of which, according to Lea (1946), are approximately 0·75 of the numbers of secondary electrons for primary electrons of energy greater than about 5 keV. As the secondary electrons will produce very few tertiary electrons of energies greater than 100 eV, the number of electrons with energies in excess of 100 eV will be about 3 per cent of the total number of electrons liberated. Bethe (1933) has shown that when the energy of the primary electron is much greater than that of the secondary, the

number of secondary electrons produced in unit path is inversely proportional to the square of the energy of the secondary electrons. Bethe suggests that this expression should hold down to secondary electron energies of about 70 eV. Massey and Burhop (1952, page 174) show the calculated velocity distribution for the slow electrons ejected in ionizing collisions of electrons of 25 to 300 eV energy with helium atoms. The most probable velocity corresponds to an energy of only 4 eV, and the most probable energy will not be very different.

So far we have considered the energy distribution of the electrons *liberated* in ionizing collisions. Such experimental evidence as is available deals with the electrons *emerging* from a surface bombarded with electrons. The work of Rudberg (1936) and Kollath (1941) shows that the energy distribution is sharply peaked at an energy of 3 or 4 eV. A collection of experimental values of most probable energies of emission by Massey and Burhop (1952, page 319) shows values lying between 2 and 6 eV with a mean of 3·5 to 4 eV. McKay (1948, page 82) states that the velocity distribution is similar, although it does not correspond exactly, to a Maxwellian distribution. There is general agreement that the energy distribution is practically independent of the primary electron energy over a wide range. Bethe's calculations (1933, page 517) give theoretical support to this experimental finding. There is, however, a considerable variation in the experimental values of the most probable energy of emission of electrons from bombarded surfaces, but theory indicates that this energy is very sensitive to changes in the work function of the emitting surface.

Summarising, we find that the electrons *emitted* from a surface bombarded by electrons have a most probable energy of about 4 eV, the energy distribution being approximately Maxwellian. For electrons *liberated* with energies in excess of about 70 eV the numbers are inversely proportional to the squares of the energies of the electrons, and the number of electrons with energy in excess of 100 eV is about 3 per cent of the total number. The energy distribution given in Fig. 2 satisfies these conditions, the number of electrons per eV interval being given by $kV^{\frac{1}{2}}e^{-V/8}$ for energies between 0 and 41 eV, and by $64{\cdot}5\ k/V^2$ for energies greater than 41 eV. The number of electrons with energy greater than 100 eV is then 3 per cent of the total.

It should be pointed out that although the peak at an energy of 4 eV and the Maxwellian distribution of velocities of the slower electrons is in fair accord with the experimental observations on electrons emitted by bombarded surfaces, the distribution of the higher energy electrons relates more to electrons *liberated within* a material rather than to those *issuing from* a surface of it. If the energy distribution of electrons liberated within a material is known, the distribution of electrons crossing a plane within the material can be calculated if isotropic emission is assumed and if the range-energy relationship for electrons in the material is known. The range-energy relationship for slow electrons is complex and very dependent upon the ionization and excitation potentials of the stopping material. There is evidence, however, that the rate of energy loss of an electron of about 100 eV energy is greater than that of much slower electrons. The probability of an ionization resulting from a collision of an electron with a molecule of low atomic number reaches a maximum of about 0·5 for some energy between 50 and 500 eV. The probability of excitation occurring will be a maximum for an energy between 5 and 50 eV. But at very low electron energies (1 eV or less) the effective cross-section often becomes very small (Ramsauer effect) and an electron may travel many free paths before becoming attached to an atom or molecule. In view of these effects the estimate of 3 per cent of the secondary electrons crossing a boundary in a light atom material having energy in excess of 100 eV is probably too large. However, the matter is further complicated by the fact that any calculation of the electron flux across an arbitrary boundary within a material will have ignored the fact that a single low energy electron might have crossed the boundary several times when undergoing multiple scatterings. This would lead to an overestimate of the number of low energy electrons crossing the surface of a cavity within a material if those low energy electrons were removed by an applied electric field on their first transit of the boundary, as must happen in some practical cases.

We may note here that on the basis of the kinetic theory, one would expect the mean free path of an electron in "air" of unit density to be about 7×10^{-8} cm, and a 100 eV electron might be expected to travel an appreciable number of free paths before becoming attached to an atom or molecule (see preceding paragraph). Lea (1946), however, gives the range of a 100 eV electron in unit density tissue as only 3×10^{-7} cm, which is only 4 mean free paths, and the ranges he tabulates for low energy electrons must be considerably too small.

NUMBER OF LOW ENERGY ELECTRONS CROSSING UNIT AREA

A dose of 1 r releases $1{\cdot}6\times10^{12}$ electrons in 1 g of air. In the absence of other information it will be

assumed that the same number is released in 1 g of other material of approximately the same atomic number. Of this number a fraction of only 10^{-3} to 10^{-4} (depending on the radiation wavelength) are primary electrons and may be ignored. The great majority of secondary electrons have energies of only a few eV. In order to obtain the flux of these electrons across unit area an estimate must be made of their range. The minimum must be 1 mean free path, and from kinetic theory this is about 7×10^{-8} cm in unit density light atom material. As stated previously, low energy electrons will probably travel a considerable number of free paths before becoming attached to an atom or molecule. There is some experimental evidence that electrons produced by an ionizing particle travel about $1{\cdot}5\times10^{-6}$ cm in unit density material before becoming attached to an atom or molecule (Klemperer, 1927; Jaffé, 1913, quoted by Lea, 1947), *i.e.* about 20 mean free paths. Assuming this to be very roughly correct, the total range of the low energy electrons produced in 1 g of unit density light atom material by a dose of 1 r is $1{\cdot}6\times10^{12}\times1{\cdot}5\times10^{-6}=2\times10^{6}$ cm, and the number of these electrons crossing 1 cm^2 will be 2×10^{6}. However, only half this number, namely 1×10^{6}, will cross each cm^2 of the surface of a cavity *from* the material *into* the cavity instead of *vice versa*. Even this number will probably be an overestimate of the electrons available for producing a current in an evacuated cavity in an irradiated material, because the argument presented in the previous section about electrons being removed by the electric field on their first transit of the boundary, will again apply.

An entirely different approach may be made to this problem. Trump and Van de Graaf (1947) have measured the number of electrons emitted by various materials when bombarded by electrons of energies from about 50 keV to 300 keV. The secondary electrons had energies mostly below 20 eV (true secondaries) or over 800 eV (reflected or scattered primaries). For a primary electron energy of 50 keV the number of true secondaries emitted by graphite was about 0·12 times that of the primary electrons. At primary energies of 100, 200 and 300 keV, this fraction, δ, was about 0·06, 0·04 and 0·03 respectively. We will assume that these values of δ apply whatever the direction from which the electrons approach the boundary of the material. The mean energy of the primary electrons at a point in water irradiated by radium γ rays is such that δ would be 0·03 or slightly less. The number of primary electrons is $1{\cdot}7\times10^{7}$/cm^2/r (Lea, 1946, page 32), so the number of low energy secondary electrons will be $1{\cdot}7\times10^{7}\times0{\cdot}03=5\times10^{5}$/cm^2/r. For water irradiated with 200kV X rays, the mean energy of the primary electrons crossing a plane within it is about 30 keV (Cormack and Johns, 1952). An extrapolation of the results of Trump and Van de Graaff (1947) indicates that δ for electrons of this energy would be about 0·17 in the case of graphite. The number of primary electrons/cm^2/r is approximately 3×10^{6}/cm^2/r for 200 kV X rays (Lea, 1946, page 32), so the flux of low energy electrons is $0{\cdot}17\times3\times10^{6}=5\times10^{5}$/cm^2/r, the same figure as obtained for radium γ rays. This should be compared with the number 1×10^{6} obtained by the other method earlier in this section. Considering the nature of the data used the agreement is remarkable. We will adopt the value 5×10^{5}/cm^2/r, as we consider it to be more soundly based. 5×10^{5} electrons/cm^2/r is equivalent to $2{\cdot}5\times10^{-4}$ e.s.u./cm^2/r or 8×10^{-14} coulombs/cm^2/r.

Taylor (1951) quotes results for cylindrical "vacuum" chambers. With a bakelite-graphite chamber a charge of about 5×10^{-12} coulombs/r was obtained. The area of the central electrode was not stated, but assuming the results to apply to the middle size of the three chambers illustrated, the area would be about 60 cm^2 thus giving 8×10^{-14} coulombs/cm^2/r, in quite remarkable (and somewhat fortuitous) agreement with the above value.

Wilson (1953) and Sievert (1940) have reported measurements with elektron metal chambers at low pressures. With radium γ rays the primary electrons liberated in elektron metal will be recoil electrons and will have the same energy distribution as those liberated in water or graphite. Furthermore, as the number of recoil electrons liberated is proportional to the electron density, and the electron ranges vary inversely as the electron density, the number of primary electrons crossing each cm^2 per röntgen will be the same as in the case of water or graphite, namely $1{\cdot}7\times10^{7}$/cm^2/r. The results of Trump and Van de Graaff (1947) give a value of about 0·06 for the secondary emission coefficient δ of slow electrons from aluminium bombarded with electrons of energy 300 keV or more. Assuming this value of δ to apply to elektron metal, the number of slow electrons/cm^2/r will be $1{\cdot}7\times10^{7}\times0{\cdot}06=1{\cdot}0\times10^{6}$ electrons/cm^2/r. This is equivalent to 5×10^{-4} e.s.u./cm^2/r. Table I has been derived from Figs. 4A – 4E and Table I in the paper by Wilson (this Journal, page 158). The electrode area assumed was the mean of the areas of the two electrodes, and this may have led to some error in the case of chamber 4 and electrode 2 since this combination had electrodes with an area ratio greater than 2 to 1. From Table I it will be seen that the mean value of the slow electron

emission is about 5 to 6×10^{-4} e.s.u./cm²/r, in good agreement with the value for elektron metal derived above.

TABLE I

E.S.U./CM²/R EMITTED BY ELEKTRON METAL (DERIVED FROM WILSON, THIS JOURNAL, PAGE 158).

Chamber	Electrode	Collecting Voltage	
		10 volts	50 volts
1	1	$5{\cdot}0 \times 10^{-4}$	$8{\cdot}1 \times 10^{-4}$
2	1	4·1	6·2
3	1	4·5	6·1
4	1	4·4	6·7
1 to 4	1	Mean = 4·5	Mean = 6·8
4	2	2·1	4·1

A similar calculation may be made using Sievert's results as replotted and extrapolated by Wilson, if it is assumed that the radius of Sievert's chamber was large compared with the electrode separation of 0·025 cm, for then the volume and surface area are directly proportional. The electron current measured is found to correspond to emissions of 2·3, 3·0 and $5{\cdot}3 \times 10^{-4}$ e.s.u./cm²/r at chamber voltages of 11 to 6, 45 to 25, and 97 to 50 volts, respectively. There is again quite reasonable agreement with the value of 5×10^{-4} e.s.u./cm²/r derived indirectly.

MEASUREMENTS AT LOW, BUT NOT ZERO, PRESSURES

Consider first the effect of small gas pressures on the electron currents discussed in the previous sections. While the mean free path of electrons in the gas is large compared with the inter-electrode distances, the effect of the filling gas must be small. Although it does not seem possible to give an exact account of the effect of collisions of the slow electrons with the gas molecules, we will assume that about as many electrons are deflected towards the measuring electrode as are deflected away from it. An increase of gas pressure will then only have the effect of slowing down these slow electrons, and making their deflection into the positive electrode more probable. In general, an increase in gas pressure would seem to increase the proportion of slow electrons deflected towards the positive electrode.

Consider next the true ionization in the gas. The electrons released in the gas will have an energy distribution not very different from that shown in Fig. 2, *i.e.* most will have energies in the range 0–30 eV. Some of these electrons will be emitted in the direction of the negative electrode, and they will reach this electrode if (i) their range is great enough, and (ii) their energy exceeds the proportion of the chamber voltage they have to overcome. The chamber voltages employed in measurements at low pressures have been kept small in order to avoid ionization by collision. Sievert and Wilson have even used voltages below the minimum ionization potential of the filling gas to ensure that no ionization by collision could be produced. Even at the higher chamber voltages used by them, it may be inferred from the linear relationship between measured current and pressure observed experimentally, that ionization by collision, even if present, was very small. Because of the low collecting voltages employed, an appreciable proportion of the electrons released in the filling gas can reach the "wrong" (negative) electrode, if their ranges exceed the chamber dimensions. This proportion will remain constant until the pressure rises to the level at which the ranges become less than the inter-electrode distances. Thereafter an approximately constant *number* of electrons will travel to the negative electrode, since the number formed will be proportional to the pressure, while the range, and therefore, approximately, the volume from which electrons may reach the negative electrode, will vary inversely as the pressure.

The ionization-pressure curve would therefore be expected to have a slope which is a constant fraction of that obtained in the region of atmospheric pressure, so long as the ranges of the electrons liberated in the gas are greater than the inter-electrode distances (*cf.* Wilson, *loc. cit.* Figs. 1 and 4A – 4E). Thereafter, as the pressure increases the slope should increase, until such time as the electrons "lost" to the negative electrode are an insignificant proportion of the total number formed.

Since, in general, the outer wall of an ionization chamber will have a greater area than the central electrode, the number of electrons lost to the negative electrode will be greater when the outer wall is negative than when the central electrode is negative. The slope of the ionization-pressure curve should, therefore, be less at low pressures when the outer wall is negative than when it is positive.

The mean free path of an electron in air at a pressure of 1 mm Hg is about 0·4 mm. If we assume that the range of a low-energy electron is very roughly 20 mean free paths, the range would be about 8 mm. Thus in an ionization chamber with an electrode separation of 1 mm, we would expect the ionization-pressure curve to have a constant small slope up to pressures of about 8 mm Hg, and at higher pressures to have a gradually increasing slope until the electron loss to the negative electrode was a negligible proportion of the total number of electrons liberated. These figures are, of course, subject to

the same considerable uncertainty associated with the "range" of a low-energy electron.

THE ASYMMETRY OF THE VOLTAGE-CURRENT CURVE AT LOW PRESSURES

A characteristic feature of most measurements at low or zero pressures is the asymmetry of the voltage-current curve. Taylor (1951, Fig. 13) gives an example of a grossly asymmetric voltage-current curve for a vacuum chamber, while Clarkson (1941, Fig. 6) gives a curve obtained at a low gas pressure. Both curves relate to chambers with coaxial cylindrical electrodes. For the vacuum chamber, at least, the voltage-current curve should be calculable using the equations given in an earlier section of this paper, if both the energy and the spatial distributions of the electrons emerging from the chamber walls are known. In the case of a spherical chamber the spatial distribution need not be known, and we have calculated the voltage-current curve for a spherical chamber having an outer wall of radius three times that of the central electrode, assuming the energy distribution of the electrons is that shown in Fig. 2. The resulting voltage-current curve is shown in Fig. 3. The gross asymmetry will be noted, as will the high negative voltage required to produce saturation.

In Clarkson's experiments it is possible that ionization by collision was a complicating factor. The field strength near the very thin central electrode would have been considerable at the high voltages used, and any ionization by collision would have been greater when the central electrode was positive and all electrons collected by it had to pass through this intense field, than when the central electrode was negative and only those electrons emitted from it or released from the gas in its immediate vicinity would have been subjected to this strong electric field. It is probably ionization by collision that is responsible for the steep increase of current he observed at the highest negative voltages applied to the outer wall of the chamber.

Wilson (1953) obtained less asymmetric voltage-current curves. In his experiments the electrodes did not have very dissimilar areas, and this would tend to reduce the asymmetry of the voltage-current curves. A further complicating factor, which might give a vertical shift to the curve, is the strong forward concentration of the fast primary electrons released by the γ rays used. There was probably a considerable nett transfer of these fast electrons from one electrode to the other. Nevertheless, Wilson's saturation curve (Wilson, *loc. cit.*, Fig. 3A) for chamber 1 and electrode 1 (ratio of areas $=1{\cdot}36$) gives evidence of a saturation plateau at both positive and negative chamber volts, whereas his curve (Fig. 3B) for chamber 4 and electrode 2 (ratio of areas $=2{\cdot}2$) has a definite plateau for positive chamber volts but no indication of one at negative-chamber volts.

VARIATION OF IONIZATION WITH VOLUME AT CONSTANT PRESSURE

Although Sievert's (1940) review of experiments designed to test ionization chamber theory indicates that more workers have varied the chamber volume at atmospheric pressure than have made measurements at varying pressures, we feel that the majority of the former set of experiments were more a test of the air equivalence of the chamber wall than a test of ionization chamber theory. Most investigators used X rays generated at 25 to 200 kV with chambers having electrode separations of 1 to 30 mm. Under these conditions the requirement that the electrons generated in the chamber walls lose only a small proportion of their energy in crossing the air volume will not be satisfied.

However, if it were possible to overcome the very great technical difficulties of working with very small and accurately known electrode separations, investigations at atmospheric pressure would also run into the difficulties produced at low pressures by the deflection of slow electrons emitted by the chamber walls. The equations given earlier should still apply, but for all practical purposes the electrodes could be considered plane parallel at the very small separations employed.

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SUMMARY

The ionization chamber measurements of other workers at low pressures have indicated (i) that the measured current is in excess of that to be expected on the Bragg-Gray theory; (ii) that there is a residual current even at sensibly zero pressure; (iii) that the gradient of the ionization-pressure curve at low pressures is less than that at atmospheric pressure, and (iv) that the saturation curves of chambers at low pressures are often grossly asymmetrical. Effects (i) and (ii) are attributed to the deflection by the chamber voltage of slow electrons emitted from the chamber walls. Expressions are derived for the number of electrons deflected between plane, spherical and cylindrical electrodes. The numbers of electrons emitted/cm^2/r deduced from ionization chamber measurements are found to agree, within a factor of 2, with the corresponding numbers derived indirectly from other data, and are approximately 5×10^5/cm^2/r and 1×10^6/cm^2/r for graphite and elektron metal respectively irradiated by radium γ rays. The approximate energy distribution of these slow electrons is indicated.

Effect (iii) is attributed to the difficulty of achieving saturation without producing ionization by collision. At low chamber volts some ions have sufficient energy to reach the electrode of the same polarity. Effect (iv) is attributed to differences in electrode areas and the asymmetry of the electric field between the electrodes. An example of a calculated saturation curve is given for spherical electrodes. Finally it is suggested that similar effects would occur at atmospheric pressure in chambers having extremely small electrode separations.

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REVIEWS

Progress in Biophysics and Biophysical Chemistry. Edited by J. A. V. Butler and J. T. Randall, Vol. III, viii + 386 pp., 85 illus., 1953 (London, Pergamon Press), 63*s*.

This third volume of *Progress in Biophysics* well maintains the high standard set by the earlier ones. Unlike its predecessors, it contains little that will appeal "professionally" either to medical radiologists or to radiological physicists, but hospital physicists will recognise the names of I. Doniach, A. Howard, and S. R. Pelc, who write on "Autoradiography"; and the article by M. Errera on "Mechanisms of Biological Action of Ultra-violet and Visible Radiations" should be read by anyone who is following modern work on the biological action of ionizing radiations. To workers in the border-line field of medicine, chemistry and physics, this collection of reviews, each of which has a comprehensive bibliography, must be of great interest and value. In addition to those mentioned above, the subjects covered are: "Polarised Ultra-violet Microspectrography and Molecular Structure", by W. E. Seeds; "Some Physico-Chemical Studies on Viruses", by R. Markham; "Recent Work on the Application of the Theory of the Ionic Double Layer to Colloidal Systems", by F. Booth; "Microspectrometry of Living and Fixed Cells", by H. G. Davies and P. M. B. Walker; "Transport Processes and Electrical Phenomena in Ionic Membranes", by T. Teorell; and "Methods of Determining the Forms and Dimensions of Particles in Solution; A Critical Study", by C. Sadron. The editors are to be congratulated on their selection of topics and on their choice of experts to discuss them.

C. B. ALLSOPP.

Radioactive Isotopes. By W. J. Whitehouse and J. L. Putman, 1953 (Oxford, at the Clarendon Press), 50*s*.

This book on radioactive isotopes has been written to provide the non-specialist in nuclear physics with enough information for him to use radioactive isotopes intelligently in pursuance of his own problems. The authors give in the text a brief outline of atomic physics, the properties and methods of disintegration of radioactive isotopes, the radiations emanating from these disintegrations, and the instruments used in their detection and assessment. They then go on to show how these isotopes are produced, how they can be handled and finally to an indication of the scope of the fields of application of radioactive isotopes in research and industry. All these facets of the subject are covered without recourse to advanced mathematics and each chapter has a very complete appendix of references.

The authors do not claim to have written a text-book on nuclear physics, but they have fulfilled their object of providing a book full of information for beginners in the subject. Probably they should have said more about health hazards involved in the use of radioactive isotopes while in some instances the advancement in the subject has been so rapid that the text is becoming out of date.

The book should provide a useful reference book to those using isotopes, to those beginning a career in the subject, and to medical people who wish to understand the background of a subject which is more and more becoming a recognised tool in medical and biological research.

G. S. INNES.