PROBLEMS ASSOCIATED WITH THE EXPENDITURE OF

THE ENERGY OF PARTICLES AND RADIATIONS

by

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Preface

In this thesis I have described work carried out to determine the average energy expended by particles (fast and slow electrons and α-particles) in producing one ion pair, in various gases. After a short introductory chapter a critical summary of previous work is contained in chapter II, and the need for more experimental data is discussed. This part of the thesis is drawn mainly from the original literature although use has been made of previous reviews. The new proportional counter technique first proposed by Dr. S. C. Curran is described briefly.

Chapter III contains an account of an investigation carried out in conjunction with Mr. A. L. Cockroft upon the properties of glass counters and ion chambers with external graphite electrodes. The extension of the proportional counter method using slow electrons to determine the ion-formation energy of the more transparent gases (hydrogen and helium) together with a closer examination of nitrogen and air was suggested to the author by Dr. S. C. Curran. The experimental work was carried out solely by the author and is described in chapters IV and V. Several minor improvements in the technique due to the author are also discussed.

The close agreement between the results obtained with electrons/

electrons and published data for fast protons suggested the extension of the work to include ionization by α-particles and further experiments, again carried out solely by the author, are described in chapter VI.   A new expression is proposed for the variation of ion-formation energy with partial pressure and stopping power of the two components in a gas mixture.   In this connection I am indebted to Dr. G. Wyllie for several fruitful discussions.   The final numerical values tabulated on p. 106 have been adopted after full consideration of the results of this thesis together with all previous data obtained at Glasgow and elsewhere.

Chapter VII contains a review of the relevant theory; no original contribution has been made by the author.   The most recent work has been summarized in chapter VIII and I am indebted to Dr. T. J. Hardwick of A.E.C. Ltd., Chalk River, Ontario, for a private communication on his unpublished work.   The integral discussed in appendix I was evaluated by Dr. E. A. Power whom I should like to thank.   It is included in this thesis as it was necessary for the work described in chapter IV and since it may have other applications.   Appendix II contains preliminary experimental work carried out by the author.

In conclusion I should like to thank Professor P. I. Dee and Dr./

Publications

(1)   The properties of proportional tubes and ion chambers with glass envelopes and external graphite electrodes.
Cockroft, A. L. & Valentine, J. M. 1950 J. Sci. Instrum. 27, 262.

(2)   Energy per ion pair for electrons in gases and gas mixtures.
Valentine, J. M. 1952 Proc. Roy. Soc. A 211, 75.

(3)   Energy expenditure per ion pair for electrons and α-particles.
Valentine, J. M. & Curran, S. C. 1952 Phil. Mag. 43, 964.

Contents

Glass counters and ion chambers were used in

an early part of the work.   This chapter

contains an investigation of their properties.

The method of using end corrected cylinders as

proportional counters and ion chambers to

measure the average energy expenditure per ion

pair is described.   The values of V for

electrons in argon, helium, hydrogen, nitrogen,

air, oxygen and methane are determined.   No

significant difference is found in the results

obtained using ^{37}A and tritium as sources of

ionizing electrons.   Curves of ion current

against percentage of argon admixed with the

other gases are plotted.   The ratio Vgas/Vargon

is given in each case and is found to be almost

identical/

identical to the corresponding ratio for

high energy protons.   Examination of

previous work with α-particles suggests

close agreement with the values for

electrons and protons, but the need for

more precise results in the case of

α -particles is noted.

The variation of V in argon with energy

of the ionizing electrons is investigated

in the low energy region of 240 eV. to

2·82 keV. and no variation is found.   In

a similar experiment for nitrogen between

the limits 240 eV. to 46·5 keV. only a

small variation is found.   It is shown

that the empirical formula proposed by

Gerbes does not represent the variation of

V in nitrogen or air.

The experiments described in chapter IV for

electrons are repeated for ionization by Po —

α-particles./

Page

particles.   Although close agreement is

obtained between the ratios Vgas/Vargon for

slow electrons and high energy protons

small differences are noted in the case of

α -particles.   A new expression is

proposed for the variation of 1/Vmixture

with partial pressure and stopping power

of the two components in a gas mixture.

Chapter I

Introduction

In the fields of atomic and nuclear physics knowledge
of the energy of a charged particle is frequently required.   One
of the most important methods of energy measurement is obtained by
relating the ionization produced by a particle in traversing a gas,
to the original energy of the particle.   The collisions a particle
(electron, proton or α-particle) makes are essentially with
electrons, nuclear collisions being sufficiently rare to be
neglected.   If the particle is energetic enough to eject an
electron from an atom of the material it is passing through, primary
ionization takes place.   The ejected electron, or δ-ray, may
itself have sufficient energy to cause ionization, this being known
as secondary ionization.   Processes other than ionization are
available to the particle for the dissipation of energy, for
example the excitation of an atomic electron.   The photon
accompanying de-excitation may, or may not, produce ionization.
Two other non-ionizing processes account for some of the energy
lost by the particle - dissociation of molecules and increase of
thermal energy of the material.   Often it is inconvenient or
impossible to separate the contributions of the various processes
to the energy loss of the particle.   For example, one method of
energy measurement is by total absorption where the ionizing
particle/

particle is allowed to spend all its range in a gas-filled
chamber and the resulting current (steady or pulse) is detected.
For the evaluation of E, the original energy of the particle, it
is not necessary to consider the separate processes provided the
average energy expenditure for the production of one ion pair, V,
is known, and is constant over the whole length of the particle
track.   In such a case the measured current is directly
proportional to the energy of the ionizing particle.   This
method is particularly important when the energy of electrons is
required as they are scattered through large angles by collisions
with atomic electrons and so have a rather indeterminate range.
In the case of heavy particles, (protons, deuterons, α-particles
etc.) the ranges are well defined and energies may be found by
consideration of a range-energy relation.   This has been the
subject of much work, and many authors, notably Holloway &
Livingston (1938) for α-particles, and Livingston & Bethe (1937)
for protons, have given range-energy relations.   The α-particle
curve has been extended to low energies by Hacman & Haxel (1943).
However, as has been pointed out by Wilkinson (1950), the low
energy curves by Holloway & Livingston and Hacman & Haxel are
essentially range-ionization curves and in order to translate them
into useful range-energy curves the value of V for α-particles
must be assumed to be independent of particle energy.

The/

The use of proportional counters for the investigation of soft radiations has been described by Curran, Angus & Cockroft (1949, a). These authors (1949, b) have investigated the resolving power of a proportional counter using single electrons produced by ultra-violet quanta. Calculation of the resolving power necessitates the assigning of a value to the average energy lost per ion pair in the methane-argon gas mixture used. The authors state that their results depend fairly critically on the value of V adopted.

In the fields of chemistry and medicine the use of ionizing radiations is of increasing importance. The biological applications of radiation have been considered by Lea (1946), and the chemical reactions induced by ionizing radiations are the subject of a review article by Dainton (1948). In these subjects in order to measure the efficiency of the radiations in producing reactions, it is essential to measure the dose rate, i.e. the rate of energy absorption in the medium under observation. In practice the intensities involved are too small for a thermal method of energy measurement and most estimates of dose rates are based on the amount of ionization produced by the radiation. Unless the medium under observation is gaseous great difficulty is experienced in obtaining a saturation current, and often an air-filled ionization chamber is used as a monitor. If the energy expenditure per ion pair in air, V air, is known, the rate of/

of ionization gives a measure in ergs of the energy absorbed.
The unit of dose employed is the roentgen which is defined as
"the quantity of X or γ radiation such that the associated
corpuscular emission per $cm.^3$ of air at N.T.P. produces, in air,
ions carrying 1 e.s.u. of electricity of either sign."   If
V air is taken as 32·5 eV., 1 roentgen corresponds to the
liberation of 2·082 x 10^9 ion pairs/$cm.^3$ of air at N.T.P.
involving an energy dissipation of 0·1083 erg /$cm.^3$ of air. Once
the number of ergs absorbed per $cm.^3$ for the ionization chamber
is known the amount of energy absorbed by 1 $cm.^3$ of any other
medium placed in the same position relative to the same source is
obtained by multiplying by its volume absorption coefficient
relative to that of air.

The above examples illustrate the importance of assigning
a value to V for various gases and of the investigation of the
variation of V, (a) with different types of ionizing particles
and radiations and (b) with the energy of the ionizing agents.
In the present work the average energy expenditure per ion pair
has been found for slow electrons and α -particles in argon,
helium, hydrogen, nitrogen, air, oxygen and methane.   An
investigation into the variation of V with energy of the ionizing
electrons in nitrogen has also been carried out.

Chapter II

Historical Survey.

The experimental determination of the average energy expenditure per ion pair by electrons of various velocities has been the subject of many investigations. Reviews of the early work have been published by Gray (1936), Binks (1936) and Compton & Allison (1936). A more recent discussion of part of the subject has been given by Gray (1944). The main object of most of the previous authors has been to find the value of V for air and to investigate the variation of V air with energy of the primary electrons. A few experimenters have measured the ionization in other gases but, in general, only the gases for which V has been found by the present author will be considered in this summary.

Three methods have been employed for the determination of V.

1.   A very direct method lies in the use of a Wilson cloud chamber. If an x-ray of known energy is absorbed by an atom of the gas in the chamber a photo-electron of known energy, E, will be produced. Then, if the expansion of the chamber is correctly made, the number of ions, N, produced by the electron is equal to the number of drops along its track. V is thus equal to E/N. Wilson (1923) and Meitner (1926) made measurements using this method but the values of V air obtained are not considered to be very/

very reliable due to the difficulty in producing condensation on
every ion without fog formation.   This problem was examined in a
careful investigation by Wilson & Dee (unpublished) who concluded
that V for air lay between 32 and 34 eV/ion pair for electrons of
9 keV initial energy.

2.   Measurement of the ionization produced by the partial
absorption of an x-ray beam in air together with the knowledge of
the x-ray beam intensity gives an indirect method for determining
V for higher energies.   Two difficulties are inherent in this
method.   Firstly, an estimation must be made of the extent to
which the x-ray beam is absorbed in the ionization chamber.
Secondly, the x-ray beam must be made mono-energetic and its
intensity measured by a method independent of ionization.   The
usual method employed is a thermal one in which the x-ray beam is
completely absorbed in a calorimeter and the heat produced is
measured.   Various micro-calorimetric methods have been used but,
as the amount of heat produced by the degradation of x-rays is
extremely small, the technique presents great difficulty.   The
early work with x-rays, up to 1926, used beams rendered
homogeneous by crystal reflection but, as the intensity available
by using this method is extremely low, the results obtained are
very uncertain.   Kulenkampff (1926) used the narrow spectral bands
near the Kα lines of various elements and made the radiation
homogeneous/

homogeneous by means of filters.   He was the first to obtain
consistent results and found that V air was constant over the
energy range 22 to 6 keV. with the value $35 \overset{+}{-} 5$ eV/ion pair.
The results of other investigators from 1926 – 29 who used similar
methods are discussed by Compton & Allison (1936) and Binks (1936).
The values of V obtained for air vary from 21 to 42·5 eV/ion pair,
and in these researches V appeared to have a constant value
independent of the energy of the ionizing electrons.   A
completely different method of tackling the problem was reported
by Steenbeck (1928) who measured the power of the x-ray beam by
using a Geiger counter to count the actual number of absorption
events in a known thickness of gas.   The work of Wilhelmy (1933)
is also worthy of note because the radiation used was much softer
(2 – 3 keV.) than that employed by other workers.   For such soft
radiation no corrections are necessary for escaping energy.   From
the results of his relative measurements Wilhelmy concluded that
V air was increasing as the energy decreased in the energy range
investigated.

In a series of investigations, Gaertner (1929 a), (1929 b),
(1931 a), (1931 b) made measurements of V for various gases using
a thermocouple to measure the energy of the beam.   He used high
pressure ionization chambers so that practically all the energy of
the x-ray beam was expended in the chamber.   The amount of
radiation escaping was allowed for by a small correction.   This

method/

method of "complete" absorption was used by Crowther & Orton (1930), (1932) to measure the value of V for various gases relative to air as a standard. Since, in making relative measurements, it is only necessary to have a constant source of x-rays and to measure saturation ion currents in the different gases these relative measurements are likely to be made with greater accuracy than absolute determinations.

Gaertner reinvestigated the problem between 1933 and 1935, (Gaertner, 1933, 1934/5, 1935), and obtained values of V for various gases relative to argon as a reference gas. The method he employed was different from that used in his earlier experiments. Two ionization chambers were used in series, the second being filled with argon and the first with the gas under observation. Saturation ion currents were measured in both chambers for different pressures in the first chamber. From these measurements the ratio V gas/ V argon can be obtained. By keeping the pressure in the chambers low Gaertner avoided the criticism, which was made of his earlier work, of incomplete saturation in the current measurements. In order to convert the relative measurements into absolute values Gaertner measured V for argon absolutely. He obtained $28 \cdot 4 \overset{+}{-} 0 \cdot 5$ eV/ion pair — a value in good agreement with his previous result of $28 \cdot 8 \overset{+}{-} 1 \cdot 0$ eV/ion pair, which was found using a different method. The values of V obtained by Gaertner are shown in col. 2, Table I.

<u>Table I/</u>

9.

Table I

Gas	V in eV.		
	Gaertner	Crowther & Orton (1)	Crowther & Orton (2)
A	28·4*	28·4	26·7
N_2	35·82	37·8	35·4
O_2	31·64	34·0	31·9
Air	35·15	37·5	35·2*
CH_4	29·78	-----	-----
CO_2	33·0	36·3	34·0

* Reference Gas.

For the sake of comparison the value of V_A = 28·4 eV. can be inserted into the ratio V air/V_A obtained by Crowther & Orton giving a value of V air = 37·5 eV. This value can then be used to find absolute values of V from the ratios V air/V gas found by Crowther & Orton. These values are shown in col. 2 of the table and are seen to differ considerably from the values obtained by Gaertner. On the other hand, if, instead of V_A = 28·4 eV being used to obtain values of V from the ratios given by Crowther & Orton, Gaertner's derived value of V air = 35·2 is used, the figures in col. 3 of table I are obtained. Only the value of V for argon is seen to differ appreciably from Gaertner's results. From this it appears that the ratio V air/V_A obtained by Crowther & Orton is inaccurate. This point was investigated very carefully by Gaertner who claims to have/

have proved conclusively that his ratio is the correct one.

The more recent work by Crowther & Orton and Gaertner rules out such values as 20 and 40 obtained for Vair by earlier workers and it would appear that Vair must have a value close to 35 eV. Of all the work carried out using x-rays that by Gaertner seems to be the most reliable and the values of V shown in col. 2 table I appear to be the most accurate obtained by the x-ray method. It should be noted that, in his most recent work, Gaertner quotes the mean wavelength of the x-rays with which he was working as 1·025 Å, corresponding to an electron energy of 12·1 keV.

3. The third method of measuring V employs a beam of electrons emitted from a hot filament. These are accelerated through a known potential and the total charge of the beam is measured together with the ionization current produced when the beam is completely absorbed in a gas. From these measurements a value of V for the gas can be found. The electrons must necessarily be accelerated in an evacuated vessel which must then be connected to the gas filled ionization chamber. Two methods of connecting the two chambers have been used. (a) For electrons of energy $>$10 keV. a thin window can be placed between the evacuated electron gun and the ionization chamber. The disadvantage/

disadvantage of this method is that the energy of the electrons
at the moment of entering the chamber is somewhat uncertain due
to losses in the window and also the production of slow secondary
electrons.   (b) Very slow primary electrons can be absorbed in a
gas at very low pressure and so for primary electron energies of
less than $\sim$ 3 keV. the ionization chamber can be directly
connected to the electron gun by means of a long narrow tube. A
good vacuum can be maintained in the accelerating chamber by means
of fast pumps.   This method is, however, also open to criticism
concerning the precise energy of the electrons as they enter the
ionization chamber since ions may be formed towards the high
pressure end of the capillary tube.   If these ions are not
collected the observed current will be too small with respect to
the energy of the electrons, as measured by the accelerating
voltage.   This would result in a spuriously high value for V.
A further difficulty inherent in the electron beam method is the
necessity of producing a homogeneous electron beam in which each
electron has the full energy corresponding to the potential
difference through which it has been accelerated.

An early measurement for Vair by this method is due to
Johnson (1917) who used slow electrons, $\sim$ 200 eV. energy, and a
direct capillary connection between the ionization and electron
accelerating chambers.   The value of V for air obtained was 36
eV/ion/

eV/ion pair with an estimated accuracy of $\pm$ 9 eV.   Anslow (1925)
performed a similar experiment in the energy range 200 - 1000 eV.
but the results obtained ($\sim$ 5 eV/ion pair for air) are not
reconcilable with other work;   a possible reason for this
discrepancy may lie in the inhomogeneity of the beam as this
factor was not investigated.

Lehmann and Osgood (1927) made a thorough investigation
into the attainment of homogeneous electron beams.   A specially
designed Faraday cylinder was used to prevent loss of primary or
secondary electrons in the electron current measurement.   The
value for Vair obtained was 45 eV/ion pair, the electron energy
range being 200 - 1000 eV.   In a further paper (Lehmann, 1927)
the results V_{He} = 31, V_A = 33, V_{H_2} = 37, and V_{N_2} = 45 eV/ion pair
are quoted.   The same value of 45 eV/ion pair was obtained by
Schmitz (1928) who used the same method with slightly faster
electrons.   Buchmann (1928) connected the evacuated chamber to
the ionization chamber by means of a celluloid window and obtained
a much lower value for Vair, viz. 31 eV/ion pair, with an
estimated accuracy of $\pm$ 3 eV.

One of the most exhaustive and accurate researches with
higher energy electrons is due to Eisl (1929).   The source of
electrons was a hot filament which was run from an A.C. potential
thus giving all velocities of electrons.   Velocity selection was
achieved/

achieved by means of a magnetic field and homogeneity to $\pm \frac{1}{2}\%$ is claimed.   A celluloid window 0·1μ thick separated the gun from the ionization chamber.   The velocity distribution of the electron beam after it had passed through the window was investigated by the method of magnetic separation with photographic recording so that the initial energy of the electrons was known with certainty.   Various other sources of error were carefully investigated by Eisl and the final result of Vair = 32·5 eV/ion pair is claimed to be correct to within $\pm 1\frac{1}{2}\%$.   A further conclusion drawn by Eisl was that Vair is constant with respect to electron energy in the range 9 – 59 keV.   In order to extend the energy range to lower values an investigation was carried out by Pigge (1934).   The use of a window is impracticable with electron energies much below 10 keV. so Pigge used the method of connection by means of a capillary tube.   This tube was, in practice, split into three sections which were carefully aligned. Following an investigation of secondary electron emission from the capillary, Pigge decided that this was a minimum when the section of the tube leading into the ionization chamber was made of graphite.   In order to keep the pressure in the ionization chamber low the dimensions of it were made large and the electrons wound up into helical paths by a magnetic field.   Electron and ion currents were measured by means of a valve galvanometer and the electron beams were shown to be homogeneous within narrow limits./

limits.   As has been pointed out the greatest difficulty in using this method lies in the formation, in the connecting tube, of ions which are not observed in the measurement of the ion current.   Pigge performed experiments to determine the magnitude of this error and estimated the necessary correction.   26 values of V are listed, corresponding to an energy range of 3·05 to 0·314 keV.   These are plotted on a graph where V is shown as a function of particle energy and a smooth curve is drawn through them indicating an increase in V from about 35 ev/ion pair at 3 keV. to 43·5 eV/ion pair at 0·314 keV.   On closer examination the experimental results appear to fall into three groups.   The first group, from 3·05 to 1·00 keV, contains 16 values of V having a mean value of 36·0 eV.   The mean square error of this group is 0·894 eV or 2·5% while the probable error is 1·7%. Pigge does not quote an experimental error for his observations but, considering the difficulty of the experiment, it is unlikely to be smaller than 2·5%.   From this reasoning the values of V between 1·0 and 3·0 keV. are sensibly constant.   From 0·77 to 0·39 keV there is a group containing 9 values of V which again have an almost constant value centering about a mean of 40·1 eV. Finally, there is a single value of 43·5 eV. for an energy of 0·314 keV.   Thus, the justification of deducing a variation of V with electron energy depends on the 10 values of V measured at energies below/

below 1·0 keV. These results contain an estimated correction of from 5 to 12%, and, considering the difficulties inherent in working with beams of very slow electrons, may be open to doubt. The experiments were performed in nitrogen instead of air to avoid oxidation of the hot filament.

Gerbes (1935) discussed Eisl's work and commented on the necessity of applying a small correction to the results to allow for an extra acceleration of the primary electrons by the field applied in the current measurement. He carried out an experiment to determine the size of this correction which, when applied to Eisl's results gave a very small variation of V with electron energy. By converting Pigge's results to refer to air and combining them with those of Eisl, Gerbes obtained an empirical formula,

$$V = 31.62 + \frac{5.27}{\sqrt{E - E_i}} \pm 0.08 \text{ eV},$$

for the variation of V with particle energy from 0·3 to 60 keV. (In Gerbes' formula, E is the initial energy of the electrons and E_i the ionization potential of the gas. E and E_i are in keV.). This gives an almost constant value for V for energies above 10 keV. but a large increase in V with decreasing energy below about 5 keV.

In a further investigation of the low energy region Freund (1935) described an ingenious method for overcoming the two major difficulties/

difficulties (inaccurate ionization current and inhomogeneity of
the electron beam) caused by the direct connection of the
ionization and accelerating chambers.   In essence, Freund measured
the number of ions formed by a group of electrons known to have the
same velocity inside the ionization chamber.   For this purpose,
it was necessary to measure electron and ion currents under the
same conditions of electric fields and gas pressures.   Electrons,
emitted from a hot filament, were accelerated through a slit B_1,
1 mm. in diameter, and then passed through another slit B_2 which
was at the same potential.   Finally the electrons passed through
a third slit B_3, which was electrically insulated from B_1 and B_2,
into the ionization chamber.   For electron current measurements a
Faraday cylinder, F, could be turned into the beam.   Throughout
the experiments the accelerating voltage, E_b, between the filament
and the slit system (B_1 and B_2) was kept constant.   Between B_2
and B_3 a variable field, Eg, opposite in sign to E_b, was applied.
Eg was varied and curves of ion current and electron current as a
function of Eg were plotted.   The gas pressure was the same for
both measurements.   In the electron current measurements there
was no voltage difference between B_3 and cage F which could cause
errors due to the migration of ions.   The conditions for the
current measurements were exactly the same up to slit B_3.   Curves
such as that shown in fig. 1 were obtained.   These were analysed
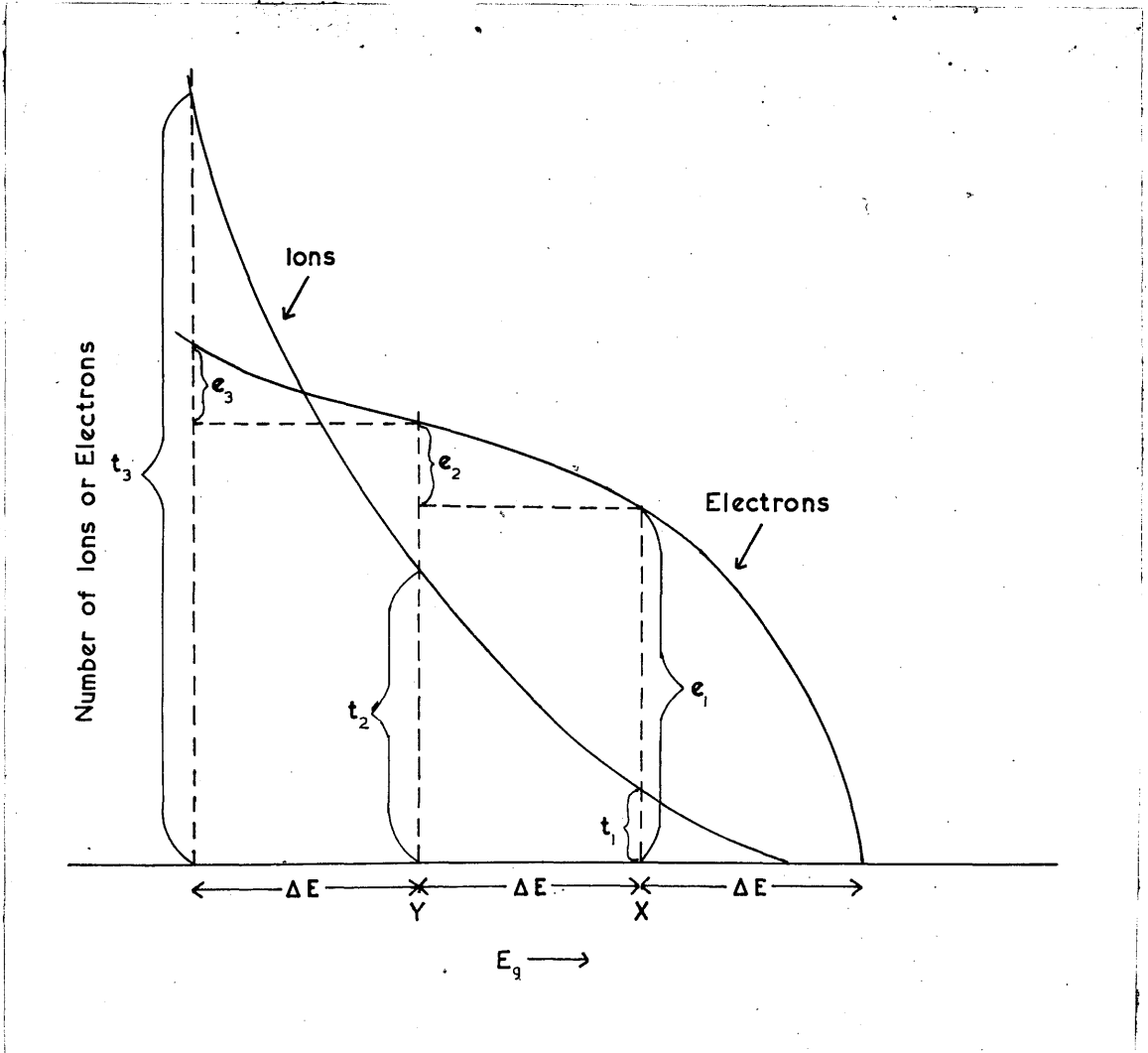by Freund in the following way.   The abscissa is divided into
energy/

Fig. 1.

Curves of ion current and electron current as a function
of Eg in Freund's experiment.

energy intervals ΔE, the respective ordinate differences on the electron curve being e_1, e_2, e_3, and on the ion curve t_1, t_2, t_3. When Eg has the value corresponding to the point X on the abscissa, e_1 electrons have energies between 0 and ΔE, and, if ΔE is small, the energy of the e_1 electrons may be taken as the average, $\Delta E/2$. These electrons create t_1 ion pairs and so the number of ion pairs created by one electron is, on average, $S_1 = {}^{t_1}/e_1$. Hence, the mean energy necessary to create an ion pair in the energy interval considered is,

$$V_1 = \frac{\Delta E}{2S_1}$$

If the opposing field, Eg, is decreased by a second ΔE to the point Y, then the average energy of the e_1 electrons is $\left(\Delta E + \Delta E/2 \right)$ i.e. $3\ \Delta E/2$. In addition, there are e_2 new electrons whose mean energy is $\Delta E/2$. Thus the number of created ions, t_2, is composed of two parts, viz. $t_2 = e_1 S_2 + e_2 S_1$ where S_2 is the average number of ion pairs created by an electron of energy $3\ \Delta E/2$ and S_1 is, as before, the number of ion pairs created by an electron of energy $\Delta E/2$.

Since $S_1 = \frac{t_1}{e_1}$, $S_2 = \frac{t_2}{e_1} - \frac{e_2 S_1}{e_1} = \frac{t_2}{e_1} - \frac{e_2 t_1}{e_1^2}$

Hence the average energy required to create an ion pair by electrons whose mean energy is $3\ \Delta E/2$ is given by,

$$V_2 = \frac{3 \Delta E}{2 S_2}$$

By/

By this differential method Freund found it possible to derive
the contribution of the different velocity groups separately, out
of the integral ion current produced.   He concluded from his
experiments, that, for electron energies between 100 and 300 eV,
V had an almost constant value about 30 eV. and that V increased
steadily with energies below 100 eV.

The above method was further refined by Breunig (1936)
who used U.V. radiations to produce electrons by a photo-electric
process and so obtained a more constant beam intensity.   Breunig
found, in agreement with Freund, a constant value for V in the
energy region 160-70 eV. and an increase of V below 70 eV.   It is
interesting to note that the constant value found by Breunig was
34 eV/ion pair, a result in good agreement with the accurate work
of Gaertner who used x-rays to produce high energy electrons.

The electron beam method was used by Gerbes (1937) to
determine the values of V in various gases.   The apparatus was
similar to that used by Eisl but incorporated several minor
improvements.   The energy range covered in the experiments was
10-40 keV. and Gerbes claimed to find a small variation, $\sim 3\%$, in
the values of V over this range.   The results were found in the
form V gas/V air and were converted to absolute values by measuring
Vair.   These absolute values for the relevant gases are shown in
table II.

<u>Table II/</u>

Table II

Gas.	V in eV.
Air	32·8
N₂	34·0
O₂	30·0
A	26·0

An interesting feature of the paper is the inclusion of a curve showing the relative ionization in a nitrogen – propane mixture.

Conclusions from the Review of Previous Experiments.

Several general conclusions may be drawn from the above review of the experiments carried out to find the average energy expenditure per ion pair by electrons in gases. These are summarized below.

1.   The large fluctuations in the value of Vair, i.e. from 20–45 eV/ion pair, obtained by earlier workers, appear to be spurious in view of the more accurate experiments performed later. There remains, however, a discrepancy in the values obtained in two experiments of comparable accuracy performed in the same energy region. Gaertner (1934/5) using an x-ray method obtained Vair = 35·2 eV. while Eisl (1929) and Gerbes (1937) found Vair = 32·5/

32·5 eV. by the method of electron beams.

2.   Although the formula proposed by Gerbes (1935) to describe
the variation of Vair with energy of the ionizing electrons seems
to have been generally accepted (e.g. by Gray, 1944, who used it
to calculate the variation in V for α-particles) it does not
appear to have a very sound experimental basis.   The validity of
the formula depends on the justifiability of fitting the results
of Pigge (1934) in the low energy region to those of Eisl (1929)
in the high energy region.   Further, the only evidence for the
rapid rise in V towards 0·3 keV, predicted by the formula, lies
in the few low energy results below 1 keV. obtained by Pigge.
These have already been criticized.   Freund (1935) and Breunig
(1936) found a constant value of Vair ~34 eV/ion pair between
~ 100 and 300 eV.   Since it is extremely unlikely that the value
of Vair (~43 eV/ion pair at 314 eV.) given by Pigge falls as the
energy decreases only to rise again below ~100 eV. it must be
assumed that the results of Freund and Breunig are in contradiction
to those of Pigge.

3.   Of recent workers only Gaertner (1935) and Gerbes (1937)
have investigated gases other than air or nitrogen.   (There is one
exception to this statement namely a measurement due to Nicodemus,
1946, who obtained a value of 26·9 eV/ion pair for electrons of
17·4 keV. in argon.   No details of this work are available.)   In
particular/

particular the values of V for the light gases, hydrogen and helium, have not been found by modern methods. These gases are important in so far as any theoretical estimate of V is likely to be made for the most simple gases.

Since the accurate determination of the energy expenditure per ion pair is a matter of considerable importance, and, as has been shown, the previous work on the subject contains several anomalies, it was decided to reinvestigate several of the more important gases using a new method. It was recognized that the use of proportional counters offered a new and powerful method for the absolute measurement of the energy expenditure for slow electrons. The first results obtained using this method were published by Curran, Cockroft & Insch (1950) and are listed in table III.

<u>Table III</u>

Gas	V in eV.
A	28·5
Air	31·0
N_2	32·0
O_2	28·8
CO_2	33·5
CH_4	28·5
C_2H_4	30·6

The/

The present author assisted in the latter stages of this
investigation and later carried out other experiments using a
similar method.   A more detailed description of the method is
contained in chapter IV.

Chapter III

The Properties of Proportional Tubes and Ion Chambers with Glass Envelopes and External Graphite Electrodes.

1. Introduction.

In part of the investigation, of the average energy expenditure per ion pair by slow electrons, carried out by Curran et. al. (1950) tritium was used as a source of ionizing electrons. It was found, however, that tritium tended to adhere to the metal surfaces of the counters or ion chambers unless it was perfectly free from water vapour. If, however, the vessels were made of glass and only a small surface area of the metal exposed to the gas filling, it was found that they were more easily cleaned and outgassed in the first instance, less likely to become contaminated, and more readily cleaned when a fresh filling was required. Maze (1946) described Geiger counters, the cathodes of which consisted of "aquadag" coatings on the external surfaces of the glass envelopes. He found that the resistivity of soda glass at normal temperatures was sufficiently low to allow the passage of the discharge current through the glass but that hard glass counters worked only at temperatures above $60^{\circ}C$. The charge to be conducted through the glass is a factor $\sim 10^4$ times smaller in the case of a proportional counter and so it was expected that proportional counters and ion chambers with hard glass/

glass envelopes would function satisfactorily at normal temperatures.

Maze type proportional counters and ion chambers were constructed. A glass proportional counter is shown in fig. 2 and the type of single-ended ion chamber extensively used in fig. 3. In this chamber the central electrode was a glass "quill" silvered on the outside to make it conducting and so the only metal part exposed to the gas filling was the brass guard tube. Due to the fact that the tubes had to be heated to assist the outgassing and decontaminating processes, and also for general mechanical strength, hard glass was used in their construction. These tubes were found to operate, but peculiar results were sometimes obtained particularly immediately after filling. For this reason an investigation into the properties of such tubes was undertaken.

2.   "Equivalent Circuit" of Glass Tube.

The equivalent circuit of a Maze-type counter is shown in fig. 4. The electrical behaviour of the glass wall is similar to that of a parallel combination of resistance R and capacity C where,

$$R = \frac{\sigma t}{A} \ \Omega \quad , \quad C = \frac{0.088 \, KA}{t} \ \mu\mu F$$

t = wall thickness (cm.)   A = surface area of wall (cm^2)
σ = specific resistivity of the glass   (ohm.cm.)
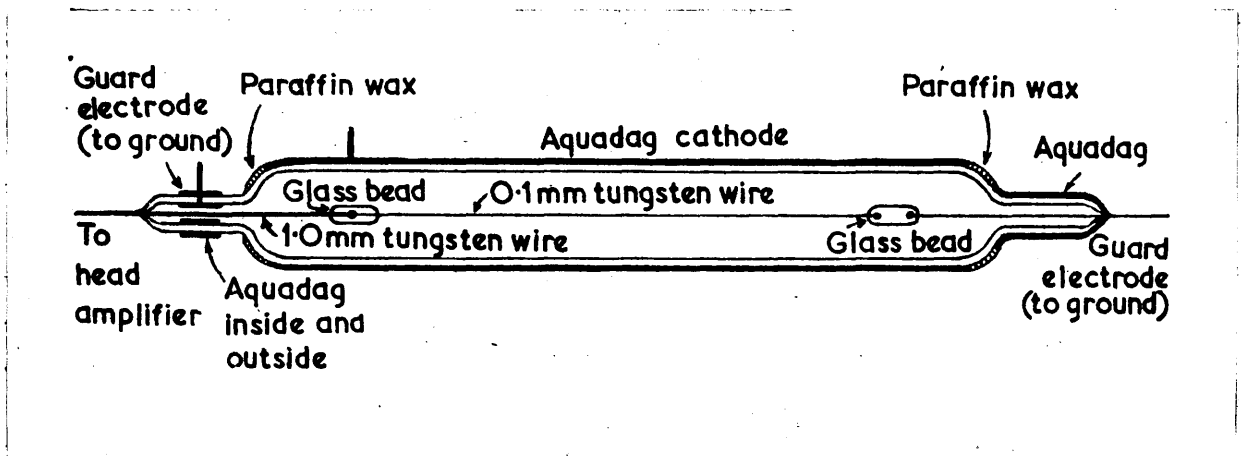K = dielectric constant.

This/

Fig. 2.

Glass proportional counter.

27.

Aquadag on outside

Paraffin wax on outside

Copper -glass seal

Paraffin wax on outside

Brass guard electrode (spring fit)

Tungsten seal

Glass "quill" tubing silvered outside
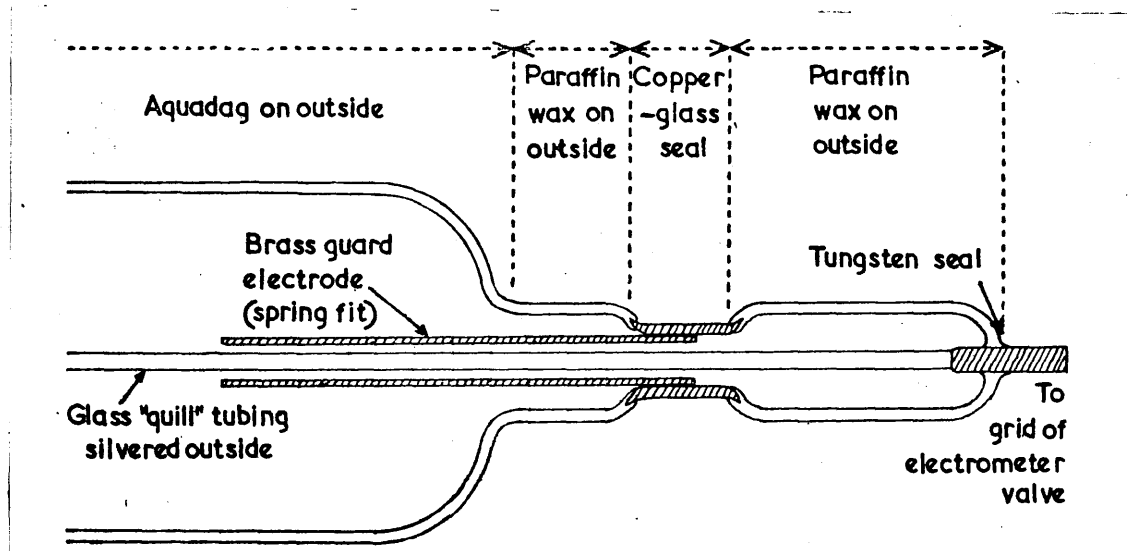
To grid of electrometer valve
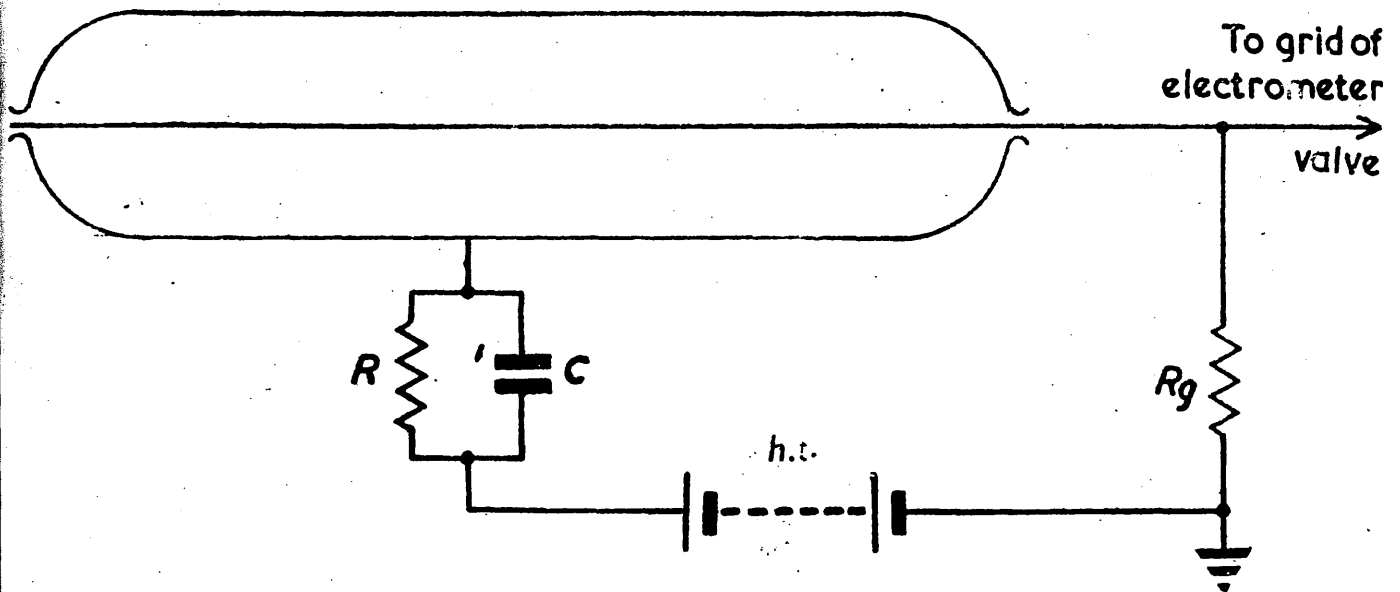
Fig. 3.

Glass single-ended ion chamber.

Fig. 4.

Equivalent circuit of Maze-type counter.

This gives the "time constant" of the counter

$$\tau = RC = 0.088 \ K\sigma \ \times \ 10^{-12} \ \text{sec.}$$

which is seen to be independent of the dimensions of the counter.

σ was measured roughly, for the glass used in the construction of the counters, in the following way. The inner and outer surfaces of a glass cylinder were coated with aquadag to within about 5 cm. of the ends. A potential difference was applied between these two electrodes and the leakage current through the glass measured. (All small currents $\sim 10^{-12}$ A, as in this experiment, and also ionization currents, were measured by means of an electrometer valve circuit. This is discussed in detail in chapter IV section 2.) Surface leakage round the ends was reduced to a negligible amount by coating them with wax. Typical values obtained from such an experiment, using a hard glass tube, are given below.

Applied voltage = 44 V.   Leakage current = 4 x 10^{-12} A.

Dimensions of tube : - length = 45 cm. circumference = 18 cm.

thickness = 0·14 cm.

$\therefore$ Resistance $R = 1\cdot1 \times 10^{13} \ \Omega$

$$\sigma = \frac{RA}{t} = 6\cdot5 \times 10^{16} \ \Omega \text{ cm.}$$

Table IV summarizes values for average sized counters of hard and/

and soft glass.   The values for K were taken from Kaye and
Laby.

Table IV.

	σ in Ω cm.	K	τ	in $^R \Omega$	^{C} in $\mu\mu$F.
Soda glass	5×10^{11}	6	$\frac{1}{4}$ sec.	$1 \cdot 5 \times 10^{8}$	1500
Pyrex brand glass	10^{17}	4	10 hr.	3×10^{13}	1000

3.   Performance of Ion Chambers and Proportional Counters.

Most of the work for which the ion chambers were primarily
developed involved currents between 10^{-12} and 10^{-11} A, since
currents in this range are readily measured with an electrometer
valve.   They are of the same order of magnitude as the average
current through a proportional counter operating at high rates
and at a gas gain which is not unnecessarily high (e.g. 20,000
counts/min. from x-rays of average energy 6 keV. with gas gain
200 gives $2 \cdot 0 \times 10^{-12}$ A.)   It is to be expected, therefore, that
the same principles will determine the behaviour of both ion
chambers and proportional tubes.   In particular, a soft glass
or metal ionization chamber filled with, say, 1 atm. air, and
with a suitable source of ionization present, will give a current-
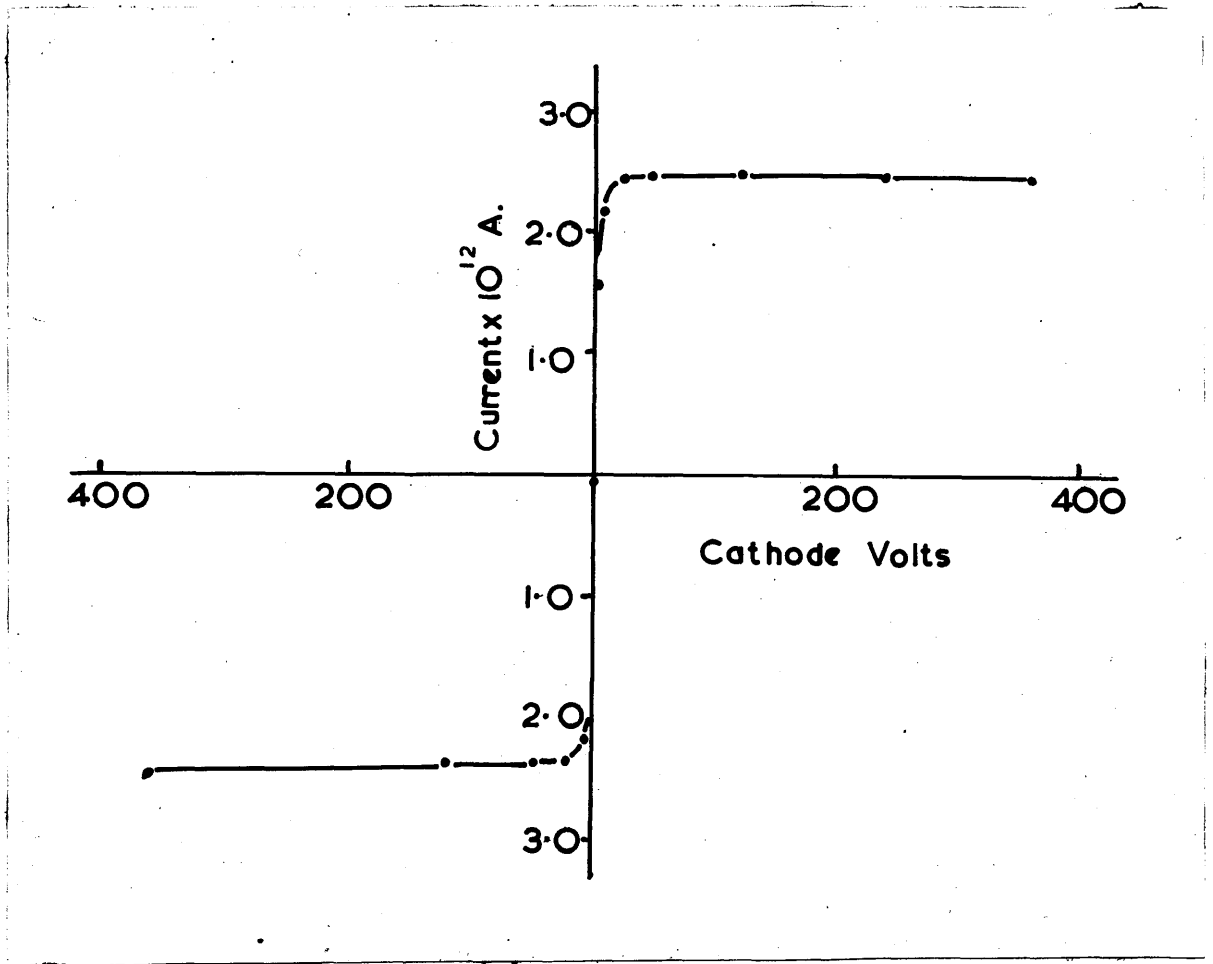voltage characteristic such as shown in fig. 5.   It can be seen
that/

Fig. 5.

Current-Voltage characteristic of a soft glass or
metal ionization chamber.

that saturation current is obtained with a very small applied voltage, that the curve passes through the origin and is symmetrical about the origin.   For such chambers the general shape and symmetry of current-voltage characteristics are independent of the history of the tubes.   When using glass chambers it has been found essential, however, to coat with wax any part of the external surface not coated with aquadag. Neglect of this precaution usually leads to trouble from spurious pulses or leakage currents.

Consideration of the values $\sigma \sim 10^{17}$ Ω cm., $R \sim 3 \times 10^{13} \Omega$ shows that the situation is quite different for a Pyrex chamber.   The voltage drop across the wall of the chamber may be expected to reach limiting values of 30 - 300 V for currents of 10^{-12} to 10^{-11} A.   The limiting value is approached exponentially with a time constant (τ) of 10 hr. and is consequently never reached in an experiment of normal duration. If the counter or chamber starts in a "neutral" state (with no potential difference between the inner and outer surfaces) the potential of the inner surface may be expected to approach that of the central collecting wire at an initial rate of 0·001 - 0·01 V/sec.   This effect manifests itself in a proportional counter as a gradual change of pulse size - usually less than 10%/hr. The very uniform size of the pulses originally observed with homogeneous x-rays becomes less uniform as the average amplitude drops.

The/

The effect in an ionization chamber can be seen from
the current-voltage characteristics plotted in fig. 6.   Curve
I was obtained when the counter was in a nearly "neutral" state.
Then with the ionizing source in position and a positive voltage
on the cathode, the tube was allowed to draw $\sim 2 \times 10^{-12}$ A for
$\sim$ 1 hr.   After that time curve II was obtained.   Since the
curve crosses the voltage axis at a voltage equal and opposite to
the potential of the inner wall, with respect to the outer, it is
seen that the passage of the current has caused a voltage $\sim$ 8 V.
to be established across the chamber wall.   Curve III was
obtained after the chamber had been left to draw $\sim 2 \times 10^{-12}$ A
for $\sim 3\frac{1}{2}$ hr. with a negative voltage on the cathode.

4.   Effects of filling etc. on Current-Voltage Characteristics.

This phenomenon of biassing the current-voltage
characteristic can be used to explain some of the peculiar results
obtained when using hard glass ion chambers.   Fig. 7 illustrates
an effect which has often been observed.   Curve I was taken
immediately after filling.   The filling process evidentally
produced a potential difference $\sim$ 300 V. between the inner and
outer surfaces.   In an unbiassed chamber an applied voltage of
say 300 V. will generally give a satisfactory saturation current
in either direction.   With this chamber, however, although
saturation current is obtained with + 300 V on the cathode an
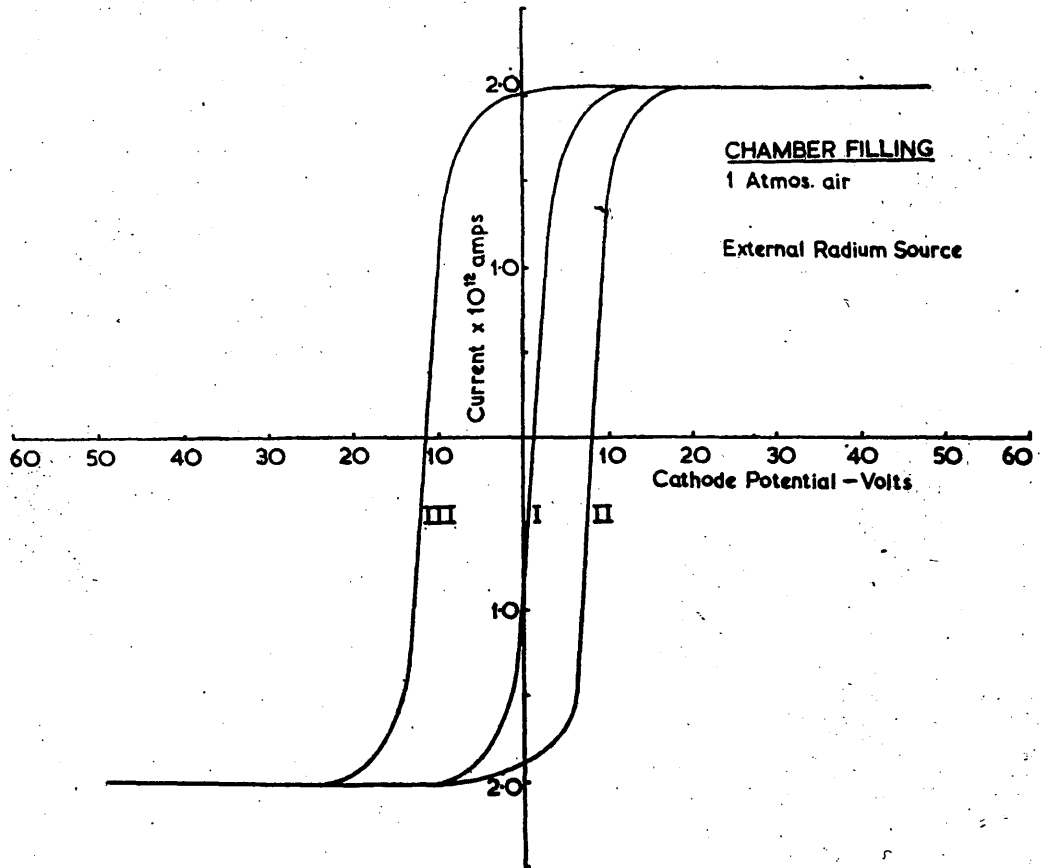applied/

Fig. 6.

Curve I,   chamber in "neutral" state.

Curve II,   after passing 2×10^{-12} A with + volts on cathode.

Curve III, after passing 2×10^{-12} A with − volts on cathode.

CHAMBER FILLING
1 Atmos. A + 1 Atmos. N₂

SOURCE
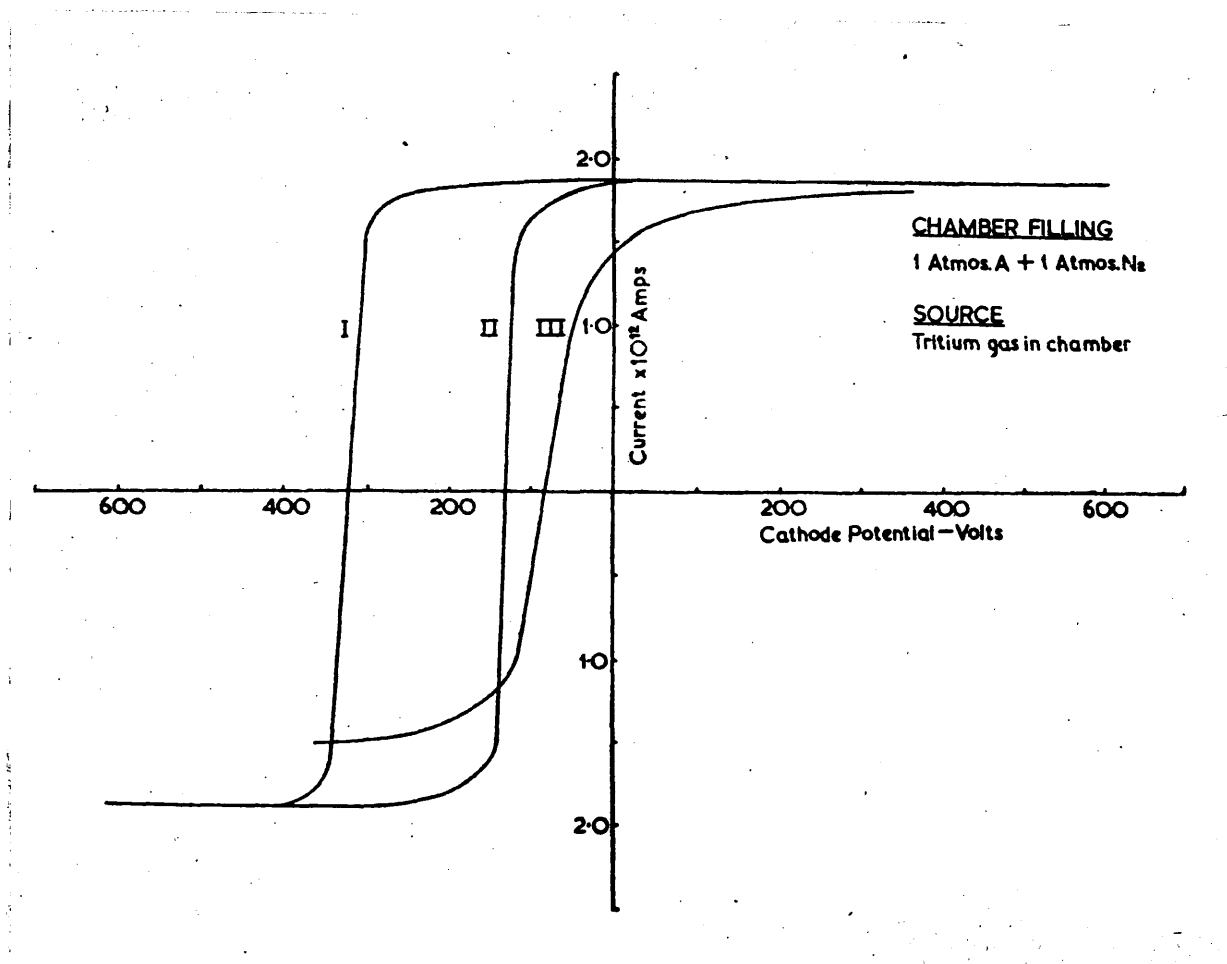Tritium gas in chamber

Fig. 7.

Curve I,   immediately after filling.

Curve II, after 20 cm. O_2 had been added.

Curve III, after passing "leak-tester" discharge over
surface.

applied voltage of - 300 V gives a current reading on the steep part of the characteristic. This reading is unreliable and often indeterminate. Curve II shows how the bias of the chamber can be altered merely by the addition of more gas. Curve III shows the unfortunate effect of running a discharge from a Tesla coil ("leak tester") over the surface of the chamber. The lack of saturation for either positive or negative applied voltages and the relatively slow crossing of the axis suggest that the surface charge on the inner wall was very patchy. This gives the explanation of another difficulty illustrated by fig. 8. Curve I was obtained immediately after filling with pure argon. True saturation current was not obtained and the curve crossed the axis very slowly. After the addition of methane, to a pressure of 10 cm. Hg., curve II was plotted and is seen to be of a more conventional shape; the curve flattens off to give saturation currents at low values (both positive and negative) of the cathode potential. Originally, the lack of saturation in case I was interpreted as being a property of pure argon which could be avoided by the addition of methane. When the procedure was reversed, however, and the initial curve taken with 1 atm. methane, curve I in fig. 9 was obtained. Curve II shows the effect of adding 10 cm. argon. The lack of saturation and general shape of curve I in figs. 8 and 9 can now be explained as being due to the patchy charge on the inner wall caused by using a Tesla coil to test/
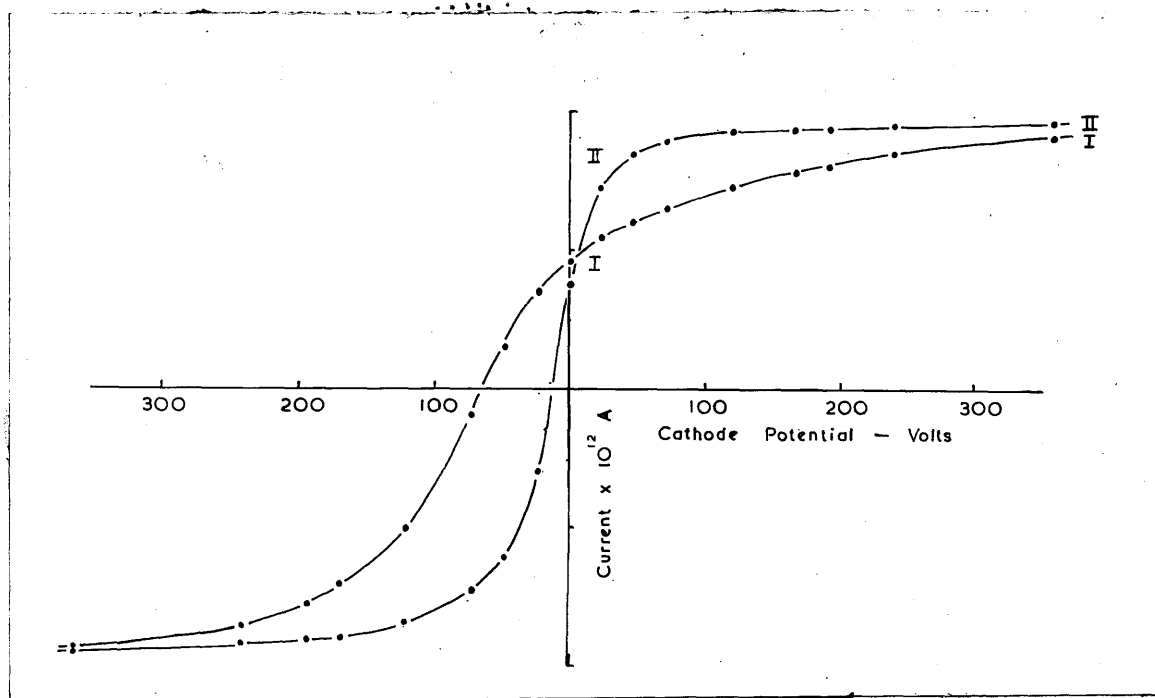
Fig. 8.

Curve I, immediately after filling with 1 atm. A.

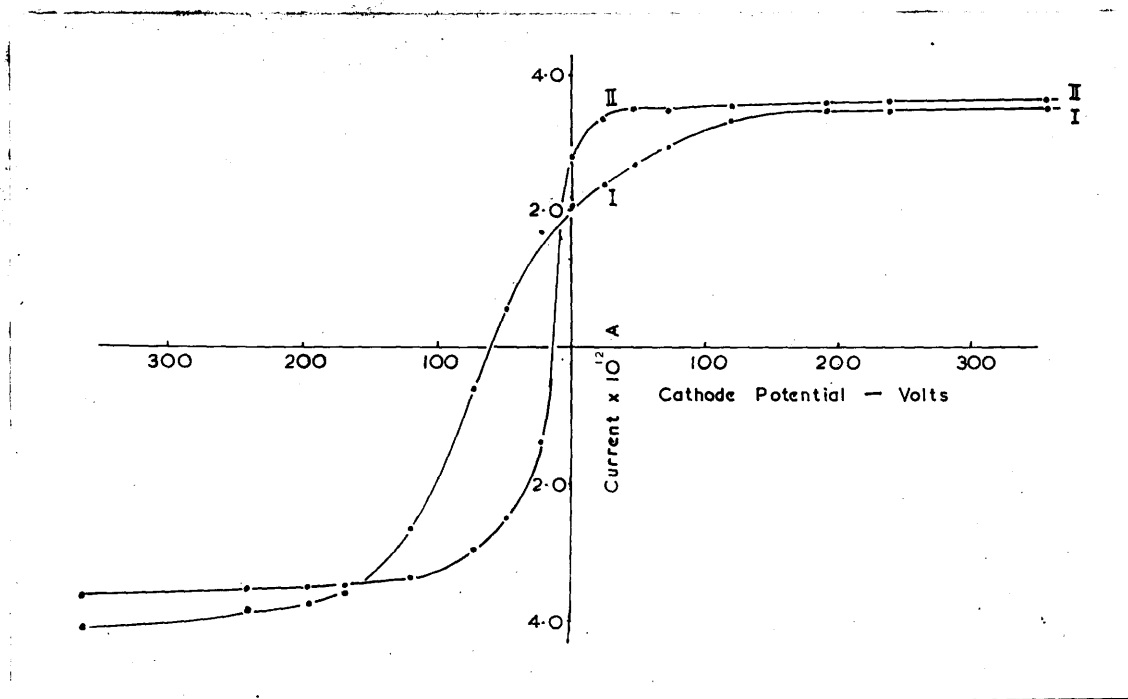Curve II, after 10 cm. CH_4 had been added.

Fig. 9.

Curve I,   immediately after filling with 1 atm. CH_4.

Curve II,   after 10 cm. A had been added.

test the vacuum before the original filling. The addition of more gas appears to have had the effect of making the charge distribution more uniform and bringing the chambers back to a nearly neutral condition.

The above examples illustrate the difficulties which prompted this investigation. In general it may be said that hard glass ion chambers can be made to function satisfactorily and give reliable results but that the shape and position of the current-voltage curve depend on the previous history of the tube. A current-voltage characteristic should be plotted for each filling to ensure that a true saturation current is obtained. Particular care must be exercised if a high frequency discharge is used for vacuum testing.

The effect of prolonged use of a hard glass proportional counter is shown in fig. 10. Fluorescent Cu x-rays were used (as described by Curran, Angus & Cockroft, 1949 a) to give a uniform distribution of pulse size in a Pyrex proportional counter. The counter was deliberately run for many hours at high counting rate until the average pulse size had fallen to about one-tenth of its original value, by which time all signs of uniformity of pulse size had disappeared. It was then set up as an ion chamber and curve I taken with an external radium source. The/

CHAMBER FILLING
10 cm CH$_4$ + 70 cm A

External Radium Source

Current x 10^{12} amps

Cathode Potential — Volts

Onset of gas multiplication
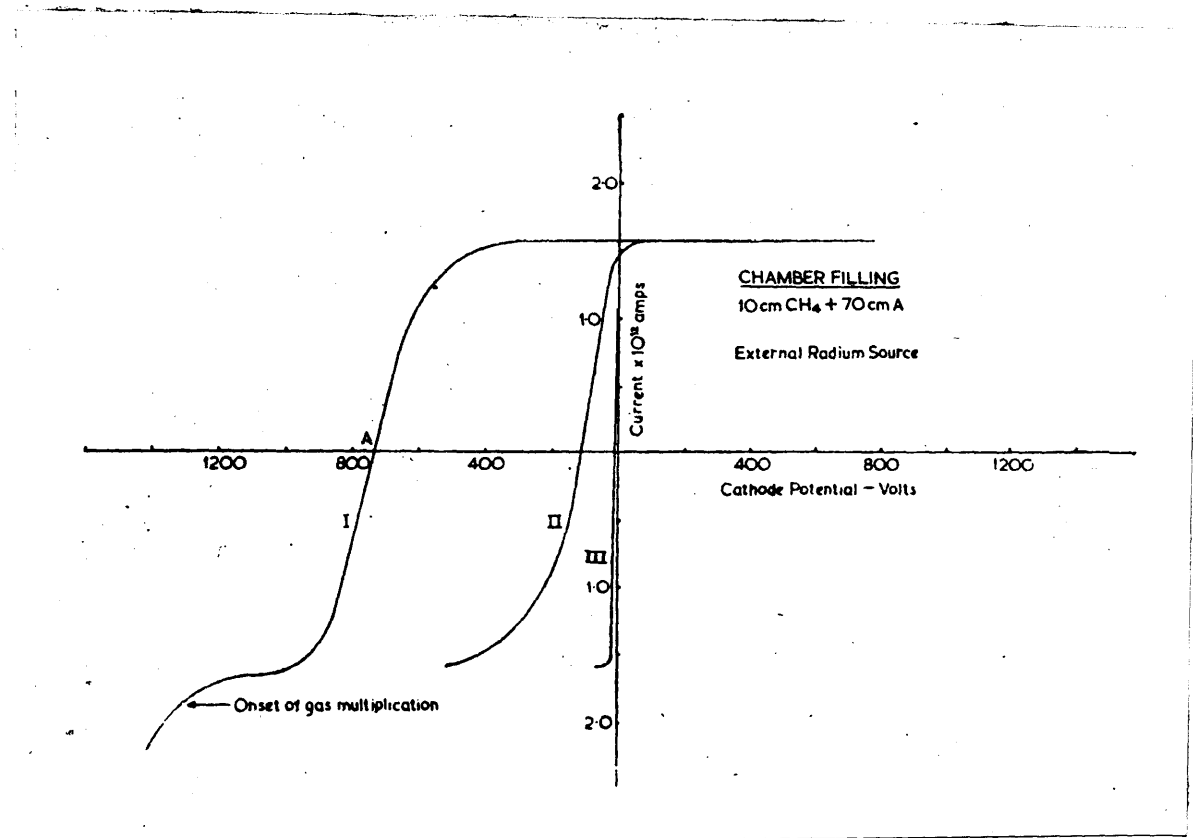
Fig. 10.

Curve I,	proportional counter after running at high gain, high counting rate for 6 hr.
Curves II and III,	as described in text showing return to neutral condition.

The inner surface had evidentally become charged in counting to a potential of 720 V. (A, Fig. 10). The surface charge was removed by leaving the counter all night near a radium source with the external graphite coating joined to the central wire. Curve II was taken the next morning and shows that the counter had almost returned to the neutral position. When curve III was taken a few hours later the process was complete.

Chapter IV

Energy per Ion Pair for Electrons in Gases and Gas Mixtures.

1.   Introduction.

The use of proportional counting tubes for the determination of the average energy expenditure per ion pair in gases has been described by Curran et al. (1950).   If a source of ionizing electrons is contained in a proportional counter the count-rate, n per second, can be accurately determined.   Then, if the average energy of the electrons is $\overline{E}$ eV and the average energy expenditure for the production of an ion pair is V eV, the rate of production of ion pairs is $n\overline{E}/V$ per second.   Further, if the tube is operated as an ionization chamber by reducing the applied voltage below the value for the onset of gas multiplication, the saturation ion current i can be measured.   The value of V can then be determined from,

$$i = ne\overline{E}/V \qquad (1)$$

where e is the electronic charge.

This method represents an important improvement over the techniques discussed in chapter II since, by using artificially radioactive isotopes as sources of electrons the difficulties, inherent in introducing a beam of electrons into a gas filled ionization chamber, are overcome.   It was decided to use the method/

method to extend and improve the first results in the following ways.

(i)   The very transparent gases, hydrogen and helium, have received very limited attention and, up to now, have not been investigated by the present method.   For the purpose of investigating these gases, and also in order to extend the range of observations to the low-energy region ^{37}A   was found to be a suitable source of electrons. ^{37}A decays mainly by K capture (Weimer, Kurbatov & Pool 1944), and, as the Auger effect is high, the source provides homogeneous electrons of energy 2·82 keV. A further advantage in using ^{37}A lies in the fact that K and L peaks are obtained (Kirkwood, Pontecorvo & Hanna 1948) and so the electron voltage per ion pair can be investigated down to $\sim$ 200 eV. for such gases as can be made to "count" well in a proportional tube.   This method is described in detail in chapter V.

(ii)   An important modification of the previous work is in the use of field adjusting tubes, as described by Cockroft & Curran (1951), to give "end-effect free" counters and ion chambers. Since a well defined counting (or collecting) volume is obtainable the accuracy of the absolute measurements is increased.   It was found that the field tubes also gave increased stability of operation and this gave more consistent results in the relative determinations/

determinations.   Because of this increased stability it was found worth while to replace the meter originally used as the standard measuring instrument, by a standard Cambridge potentiometer.   In the original experiments insufficient allowance was made for the temperature coefficient of a high resistance which was a vital part of the current measuring system.   A further refinement of the method consisted of the measurement of this temperature coefficient and the normalization of all the current readings to a standard temperature at which the absolute value of the resistance was measured.   For these reasons, it was thought worth while to use tritium, as well as ^{37}A, and to repeat some of the previous work described by Curran et al. (1950).

(iii)   The measurements were extended to include gas mixtures and curves of ion current against percentage of argon admixed with the other gases are plotted.   These mixture curves were used to find accurate relative values.   They are also discussed in chapter VI in connection with the ionization of α - particles.

2.   Apparatus.

The ionization chamber was constructed from a brass tube of internal diameter 10·15 cm. and wall thickness 0·6 cm.   The type of terminal used to correct for "end effect" is shown in fig. 11. This/
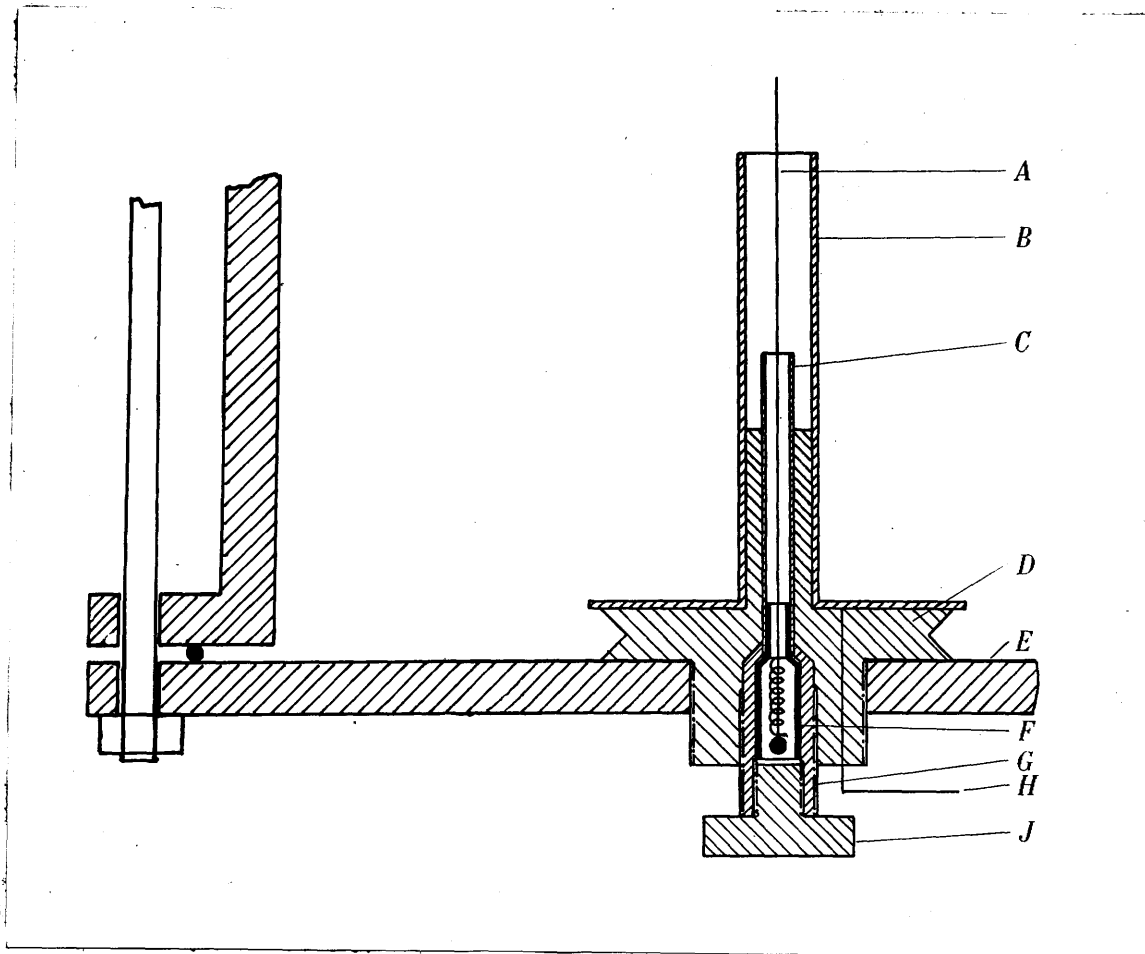
Fig. 11.

Terminal used in ion chamber. A, central wire; B, field adjusting tube; C, guard tube; D, ebonite; E, counter end; F, ebonite holder for spring; G, brass connexion to guard tube (earthed); H, lead for field tube volts; J, ebonite.

This terminal screwed into the copper end-plate the junction between then being made vacuum tight by the application of molten wax* to the ebonite thread during the screwing in process.   A vacuum tight seal between the end-piece and the flange on the main tube was effected by means of an "0" ring.   Four steel tie rods, arranged as shown in fig. 11, held the ends in position.   The chamber was evacuated and filled by means of a copper pipe (0·5 cm. inside diameter) soldered into the main tube about 5 cm. from one end.   The "tap" simply consisted of a screw clip on a piece of rubber pressure tubing which was attached to the evacuating pipe. When assembled the ionization chamber was capable of withstanding pressures in excess of 5 atm. above atmospheric pressure. Provision was made for a small window of thin aluminium foil in the centre of the tube;   when the chamber was used at high pressure the window was blocked with a thick aluminium sheet.   The distance between the ends of the field adjusting tubes was 64·3 cm. giving a collecting volume of 5200 cm.^{3}.   The central electrode was a copper wire 0·1 cm. in diameter.

The construction of the proportional counter is shown in fig. 12.   The terminal used to correct for "end-effect" is the same in principle as that shown in fig. 11, but because of its small internal diameter (1·8 cm.) the counter was constructed without

* Actually a mixture of beeswax and resin was used.
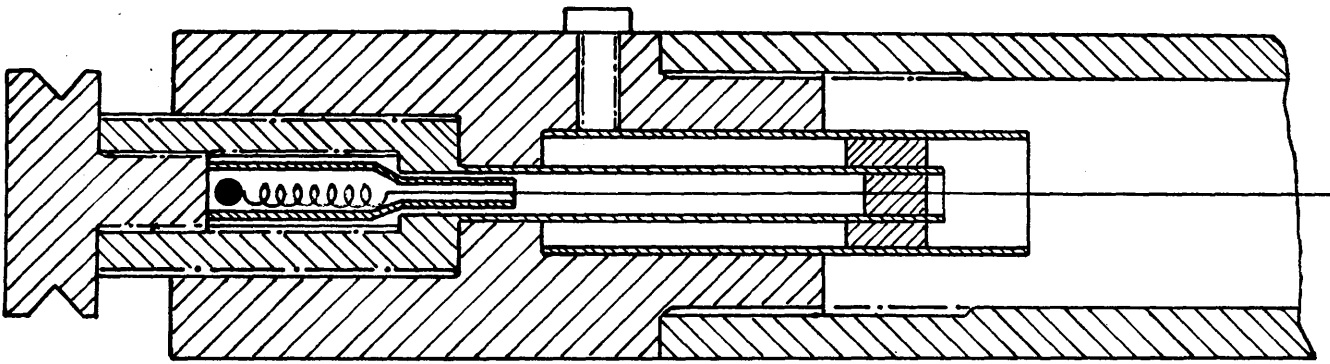This technique was employed for sealing all ebonite-brass junctions.

Fig. 12.

Proportional counter.

end-plates, the terminal screwing directly into the main tube.
The effective length of 12·45 cm. gave a counting volume of 31·4
cm.^{3}. A tungsten wire of 0·0075 cm. diameter was used as the
collecting electrode.

The absolute value of the ionization current was
determined by means of an electrometer valve, the circuit of which
is shown in fig. 13. A high resistance ($R_g \sim 10^{11} \Omega$) was
used as the grid leak of the electrometer valve and the anode
current ($\sim 10^{-12}$ A) read off on the sensitive microammeter in
the anode circuit. The standing anode current of the valve was
cancelled by means of potentiometer P which was used to set the
microammeter to a zero position in the centre of the scale before
every reading. The change of anode current due to the
ionization current caused the meter to be deflected from this
zero position. In practice this deflection was noted first with
a voltage of + 1050 V and then − 1050 V across the chamber. A
biassing voltage was applied (by means of potentiometer Q) such
that the microammeter deflected the amount between these two
readings. This bias voltage was the actually observed quantity
and it was measured on a standard Cambridge potentiometer.
(C.P. in fig. 13). Half the bias voltage was then proportional
to the ionization current. This method was adopted for the
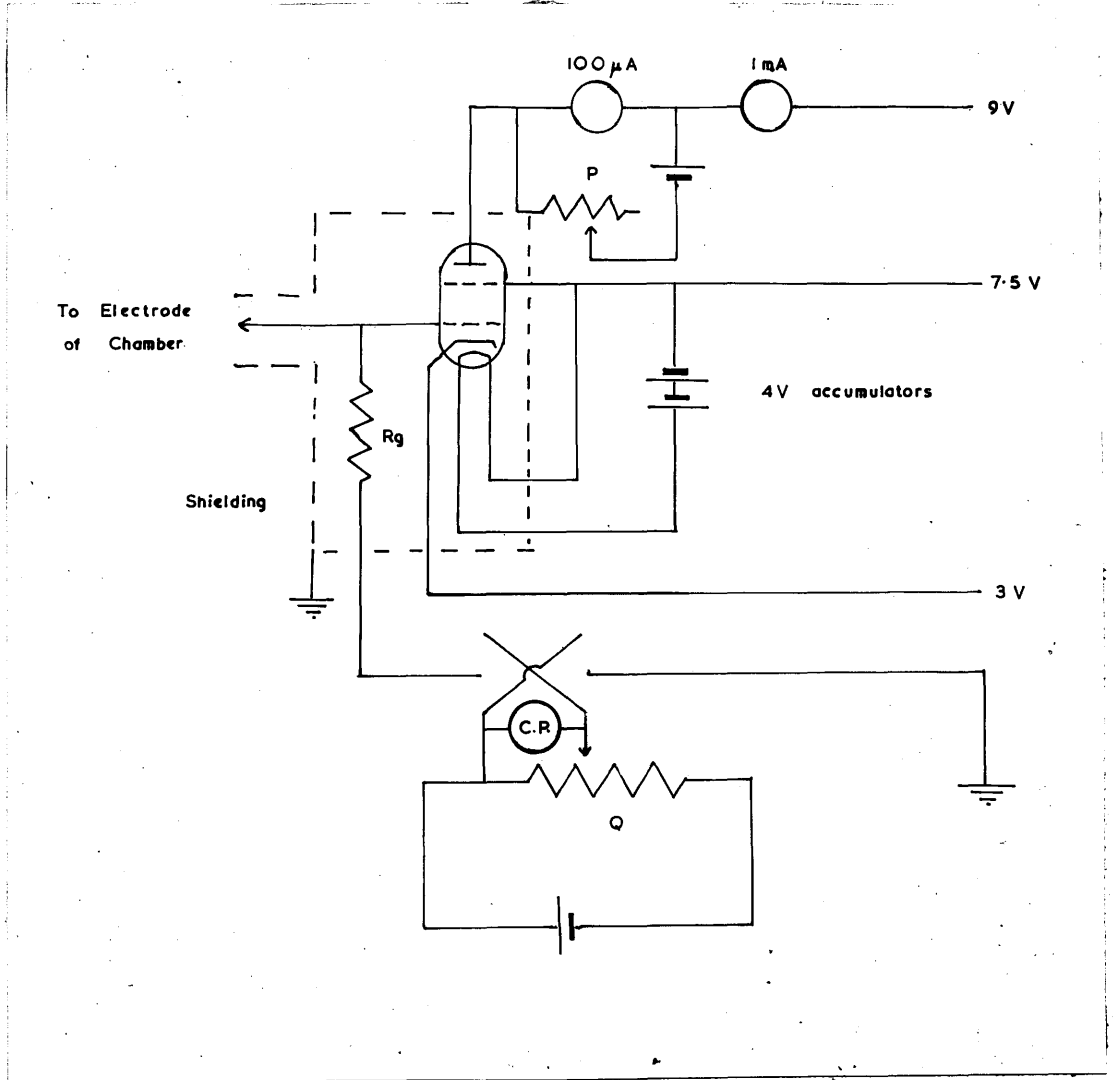absolute measurements to ensure that no error was incurred due to
uncertainty/

To Electrode
of Chamber

Shielding

Fig. 13.

Electrometer valve circuit .

uncertainty in the zero position.

The grid leak resistor was housed in a separate copper box as shown in fig. 14. The leads to the resistor were taken out of the box through distrene plugs $\sim$ 1 cm. in diameter. It was found that the resistance was temperature sensitive and in order to measure its temperature coefficient a small heating element was placed in the box below the resistor. A sensitive thermometer inserted in a rubber stopper in the lid enabled the temperature in the box to be read off at any time. A standard current ($\sim 10^{-12}$ A) was provided by the ionization chamber with attached radium source shown in fig. 15. (This standard current had been used by Curran et.al.). By varying the current through the heating element readings of the ionization current were obtained at various temperatures. The results of several runs, both with temperature increasing and decreasing, are shown in fig. 16. The resistance is seen to vary linearly with temperature between the normal working limits of 15 to 20°C. The coefficient of increase of resistance with temperature obtained from the graph is $-2 \cdot 3\%$ / $^{\circ}$C. Although the resistor was housed in a separate box it was found impracticable to control the temperature with sufficient accuracy. No hysteresis effect of resistance with temperature (for small temperature changes) was found, however, and consistent results were obtained by noting the temperature when/
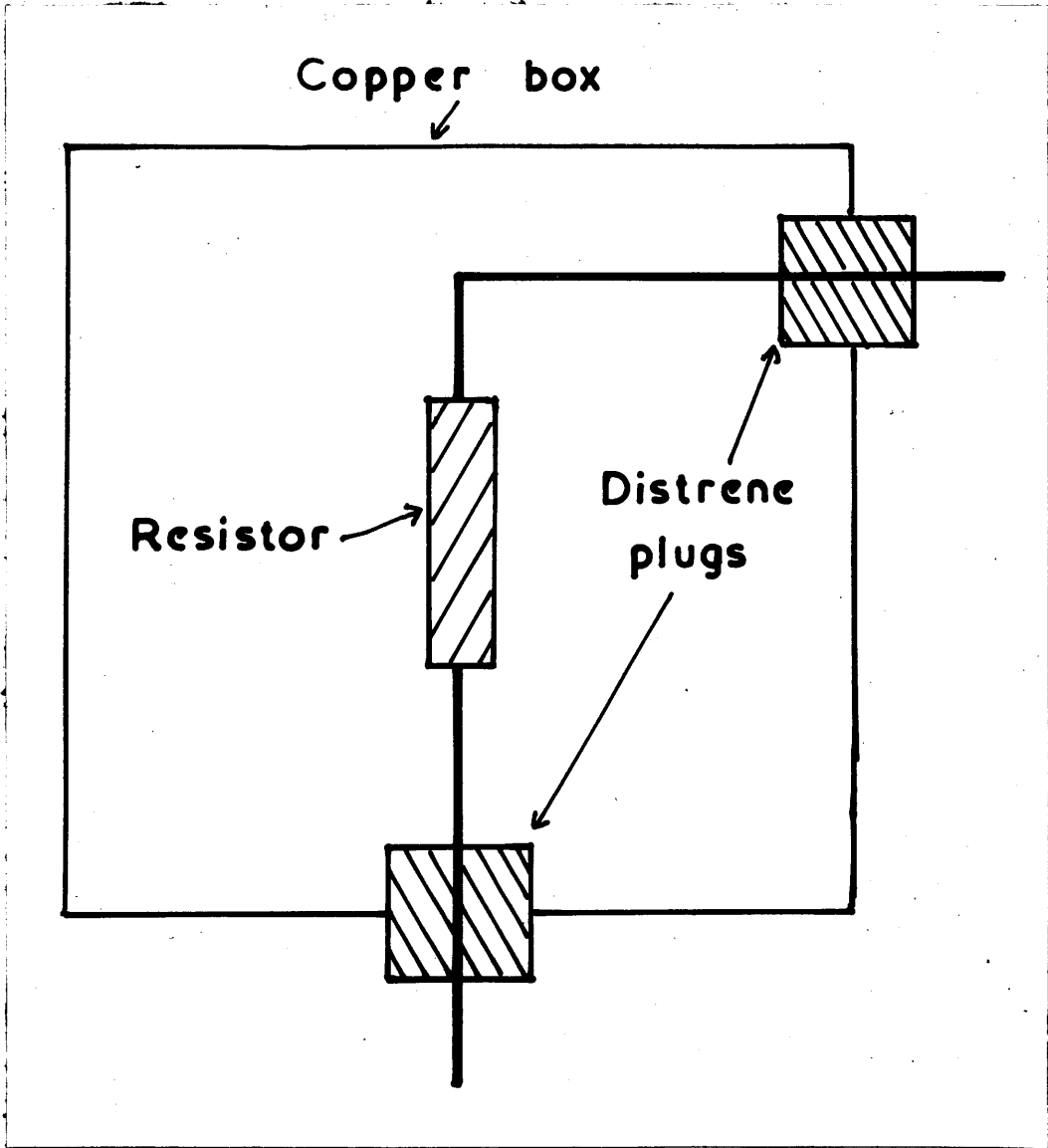
Copper box

Resistor

Distrene plugs

Fig. 14.

Mounting of Rg.

Ion chamber

Wooden
block

Cotton wool
plug

Radium source in sealed
glass tube
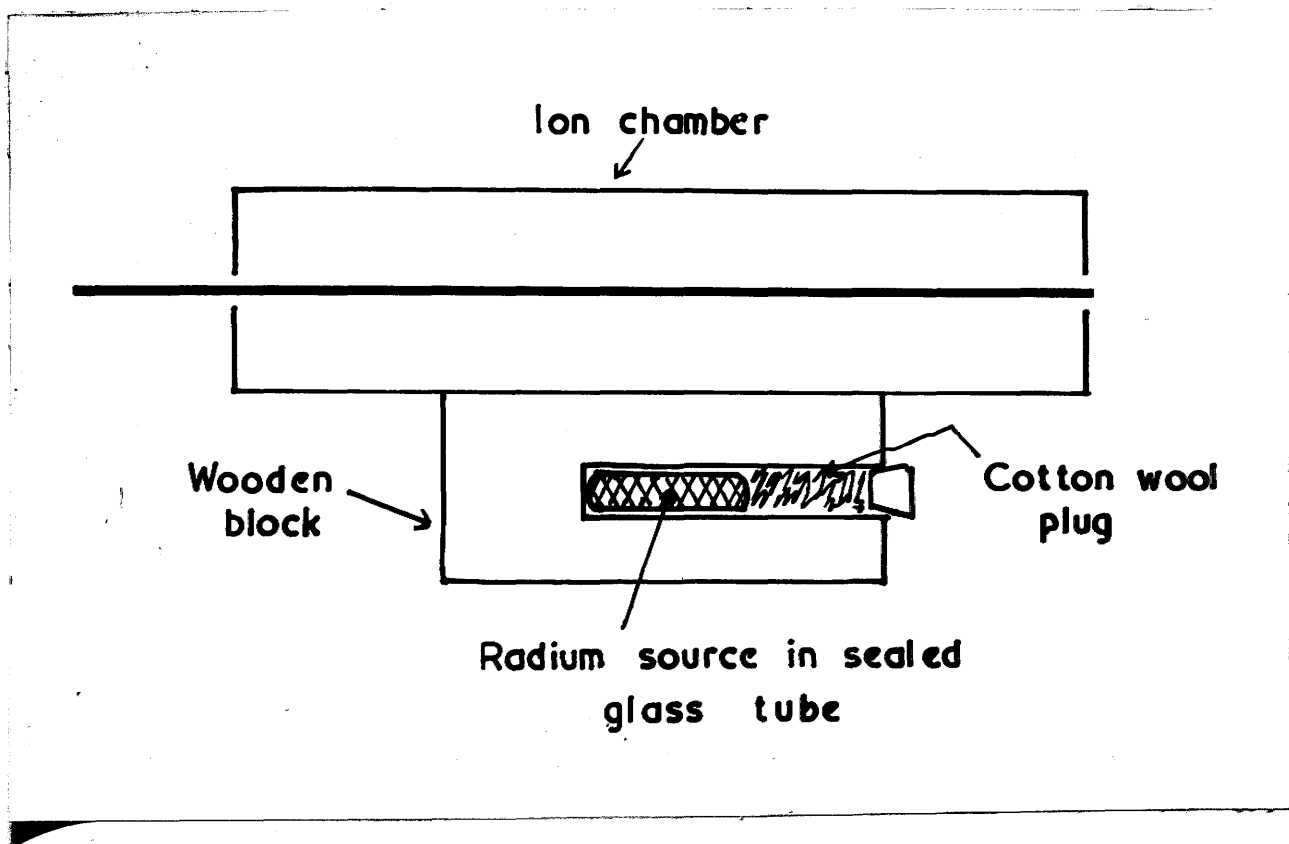
Fig. 15.

Standard current.
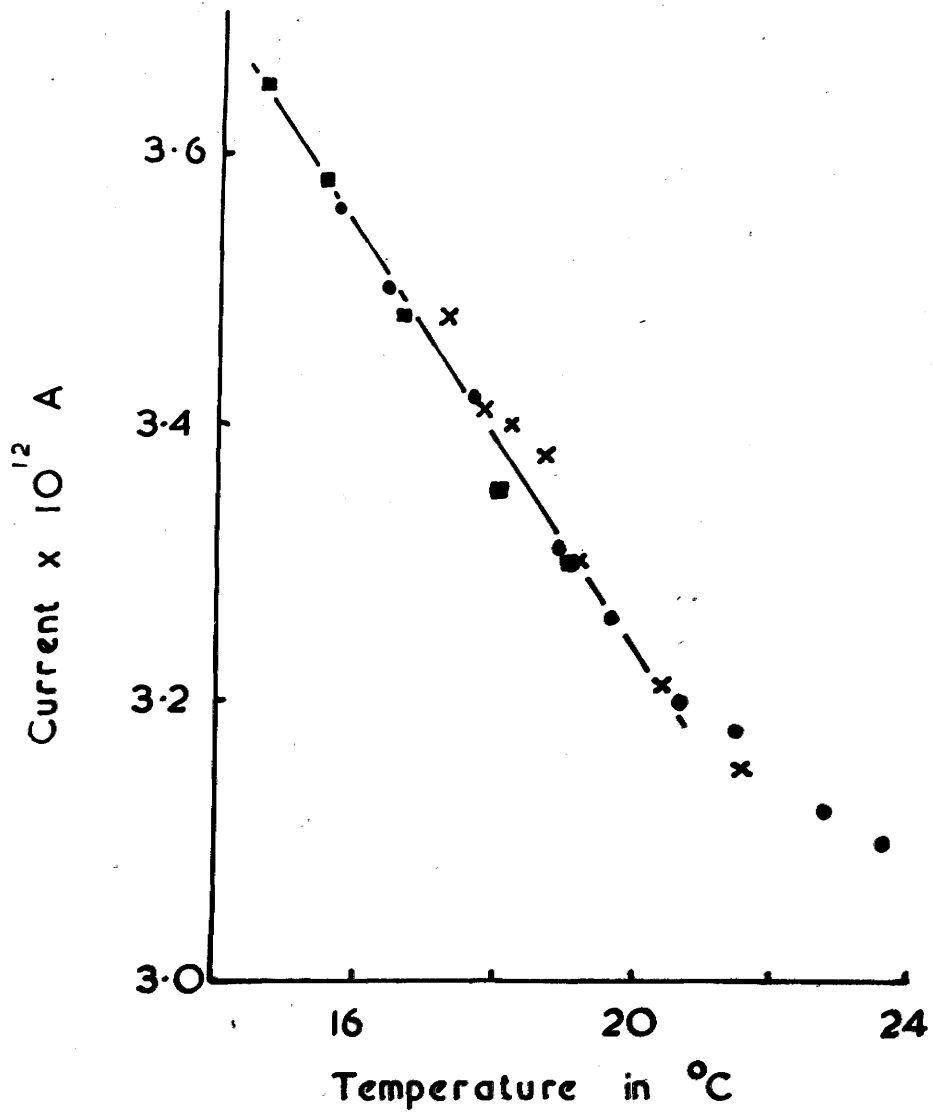
Fig. 16.

Variation of Rg with temperature.

when a current reading was taken and normalizing at $17 \cdot 65^{o}$C, at which temperature the absolute value of the resistance had been determined. This effect had not been allowed for in the previous work and is a possible source of inaccuracy. In that case use of the standard ion current probably eliminated large errors.

The absolute value of the ionization current can only be determined if the value of R_g is known. The electrometer valve circuit was used in the following way to measure R_g. The junction of a standard megohm and a resistor $\sim 5 \times 10^7 \ \Omega$ was joined to the grid of the electrometer valve, the megohm being used as a grid leak. An accurately measured potential difference of 50V was applied, from a battery, across the resistor chain. The voltage drop across the megohm was obtained by measuring the biassing voltage required to return the microammeter to its zero position. This enabled the value of the $5 \times 10^7 \ \Omega$ resistor to be calculated accurately. The procedure was repeated with a $3 \times 10^9 \ \Omega$ resistor in series with the $5 \times 10^7 \ \Omega$ resistor. After the $3 \times 10^9 \ \Omega$ resistor had been standardized it was used to measure R_g. During this experiment, instead of making soldered joints the ends of the high resistors were tied with copper wire to the required terminals. If a soldering iron was used the resistance dropped to about 2/3 of its original value and took about $\frac{1}{2}$ hour to recover.

To/

To eliminate the possibility of a systematic error in the measurements the following independent methods were used to check the value of R_γ.

(i)   The method of using intermediate steps between a standard megohm and R_γ was repeated with a conventional resistance bridge.

(ii)   A gold leaf electroscope was used to measure the time taken for a standard $1000 \mu\mu F$. condenser to discharge through R_γ. After the instrument had been calibrated, by observing the times taken to discharge through known potential differences, R_γ was determined.

No systematic differences between the values obtained by the three methods was noted and the mean value of each group was the same to within a few per cent.   The final result was considered to be correct to within $\pm 2\%$.

In all R_γ was measured three times at yearly intervals and it was found that the resistance was increasing by $\sim 10\%$ per year.   This change was negligible, however, over the period occupied in making a final accurate series of observations.   It is interesting to note that this increase of resistance with time was noted for other resistors $\sim 10^{11} \Omega$.   The actual percentage increase was peculiar to a particular resistor, but it appeared to be roughly constant for all the resistors investigated.   In order to eliminate the possibility of a discontinuous change in the value/

value of the resistance R_g was measured (using the electrometer valve method) before and after taking a final set of readings.

3.   Energy Spectrum of ^{37}A.

As described by Weimer et al. (1944) ^{37}A decays by the capture of an orbital electron. These authors reported that they detected no associated γ-rays. Since, however, the presence of a high energy tail alters so seriously the average energy of a peak distribution (as for example, in the case of ^{64}Cu discussed by Curran et al., 1950) the high energy end of the spectrum of ^{37}A was carefully investigated. A proportional counter was filled with argon to a pressure $\sim$ 60 cm. Hg. and methane to a pressure $\sim$ 15 cm. Hg. together with a strong source of ^{37}A, · $\sim$ 140,000 counts/min. The distribution was examined by means of a simple single channel pulse analyser consisting essentially of two scaling units type 1009 A. (The analyser has been described by Insch & Curran, 1951). Fluorescent x-rays of copper (energy 8·05 keV.) were used to calibrate the energy range from the immediate vicinity of the K peak to 60 keV. A separate run, calibrated at 24 keV. by silver x-rays, extended the range up to 170 keV. The background spectrum was subtracted in each case and the curves fitted. The resultant composite curve is shown in fig. 17. It can be seen that no pulses were detected above 30 keV./
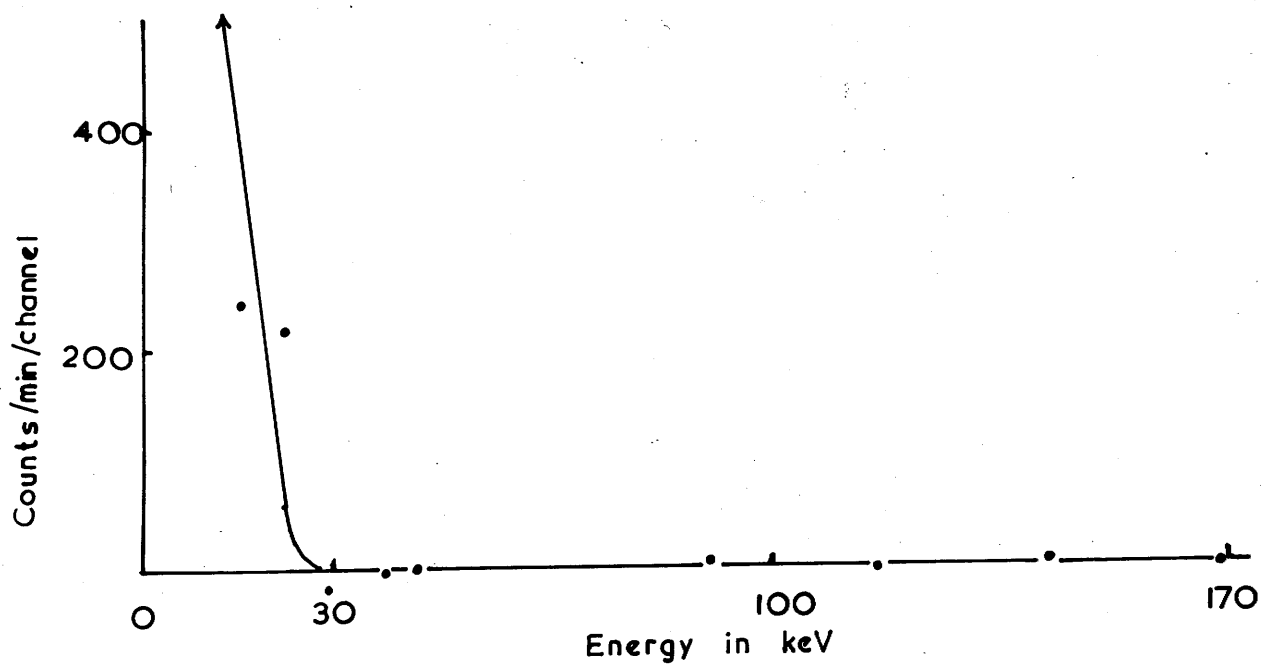
Fig. 17.

Energy spectrum of ^{37}A above 30 keV. (strong source).

keV. The rise of the curve below this energy was attributed to the existence of multiple pulses due to the very strong source used. In order to check this hypothesis a weaker source ~ 20,000 counts/min. was used and the spectrum in the neighbourhood of the peak was found to be as shown in fig. 18. Since no pulses were detected in the region between the 5 keV. point in fig. 18 and the 30 keV. point in fig. 17, it was deduced that there was no high energy tail attached to the K-capture peak from ^{37}A.

An investigation by Kirkwood et al. (1948) revealed that in about 90% of the decay processes a K electron was captured, and in the remaining transitions an L_I electron was captured. A calculation by Rose & Jackson (1949) shows that the figures for K and L_I capture are 92·5 and 7·5% respectively. The Auger electron yield for the K shell is 94%; thus in 94% of the K electron captures the full 2·82 keV. will be dissipated in the chamber. In the remaining 6% of these transitions K quanta of 2·62 keV. will be liberated together with radiations of 200 eV. energy. In the 7·5% of the L_I captures 200 eV. energy will be liberated in the chamber. It is assumed that this energy, whether in the form of electrons or quanta, is completely absorbed in the chamber. The average energy, $\overline{E}$, of the radiations can thus be calculated by considering (energy) x (number/
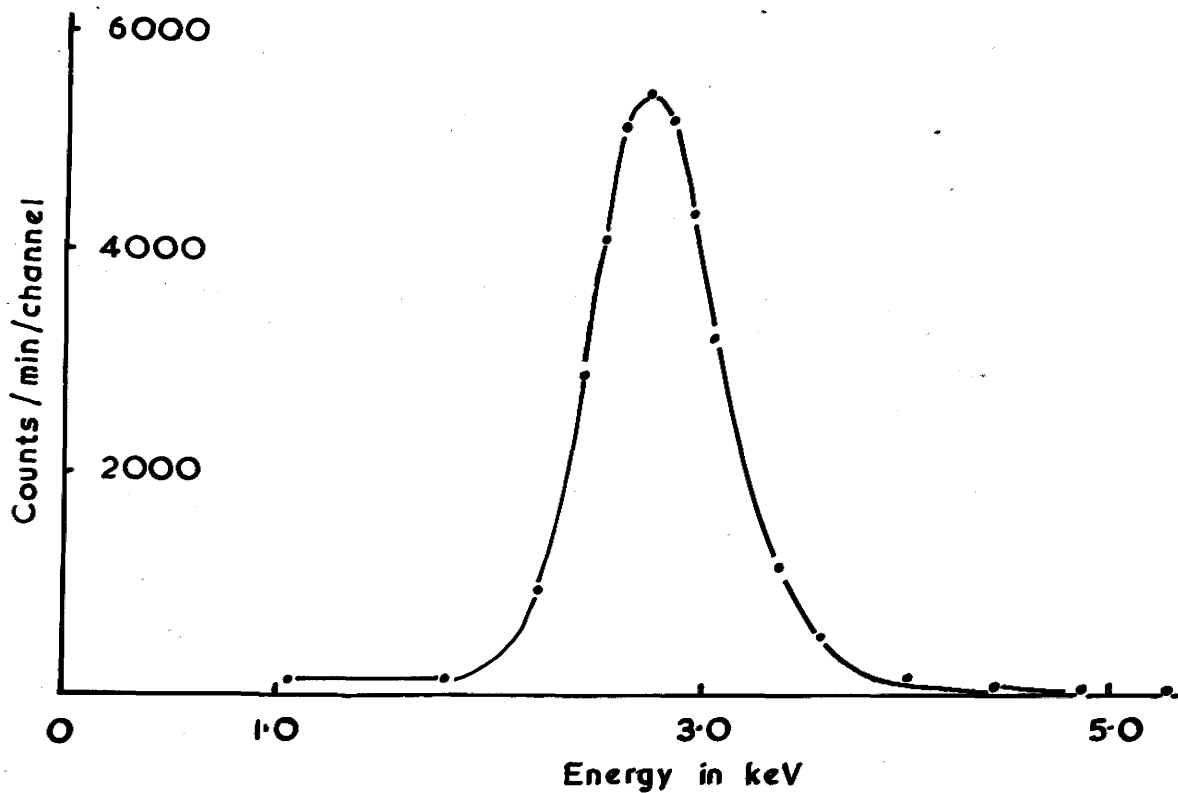
Fig. 18.

Energy spectrum of ^{37}A , 1 - 5 keV. (weak source).

(number with that energy) for say 100 transitions.   We write

$$= 1/100 \ (92 \cdot 5 \times 0 \cdot 94 \times 2 \cdot 82 \times 10^3 + 7 \cdot 5 \times 200 + 92 \cdot 5 \times 0 \cdot 06 \times 200 \\ + 92 \cdot 5 \times 0 \cdot 06 \times 2 \cdot 62 \times 10^3 \times N) \ eV,$$

where N is the fraction of the number of $2 \cdot 62$ keV. quanta absorbed in the chamber.   If P is the point, inside a cylindrical chamber, at which a quantum is emitted, then N can be evaluated by considering the function $e^{-\mu d}$, where d is the distance of P from a wall and μ the absorption coefficient of $2 \cdot 62$ keV. quanta in the gas contained in the chamber. $e^{-\mu d}$ must be integrated so that P moves throughout the volume of the cylinder and d moves over all the surfaces.   This integral can be evaluated approximately for particular values of μ .   (A more detailed discussion of the evaluation is contained in appendix I).   In the cases of hydrogen and helium μ is very small so that $N \doteqdot 0$ and $\overline{E} = 2 \cdot 49$ keV. μ is approximately the same for argon and nitrogen and $N \doteqdot 0 \cdot 80$ making $\overline{E} = 2 \cdot 61$ keV.

A correction must be applied to $\overline{E}$ to account for the natural background of the ion chamber.   This correction was determined by fitting the ion chamber with a central wire of tungsten, $0 \cdot 0075$ cm. in diameter, and operating it as a proportional counter.   The background spectrum was plotted using the single-channel pulse analyser and is shown in fig. 19.   The average/
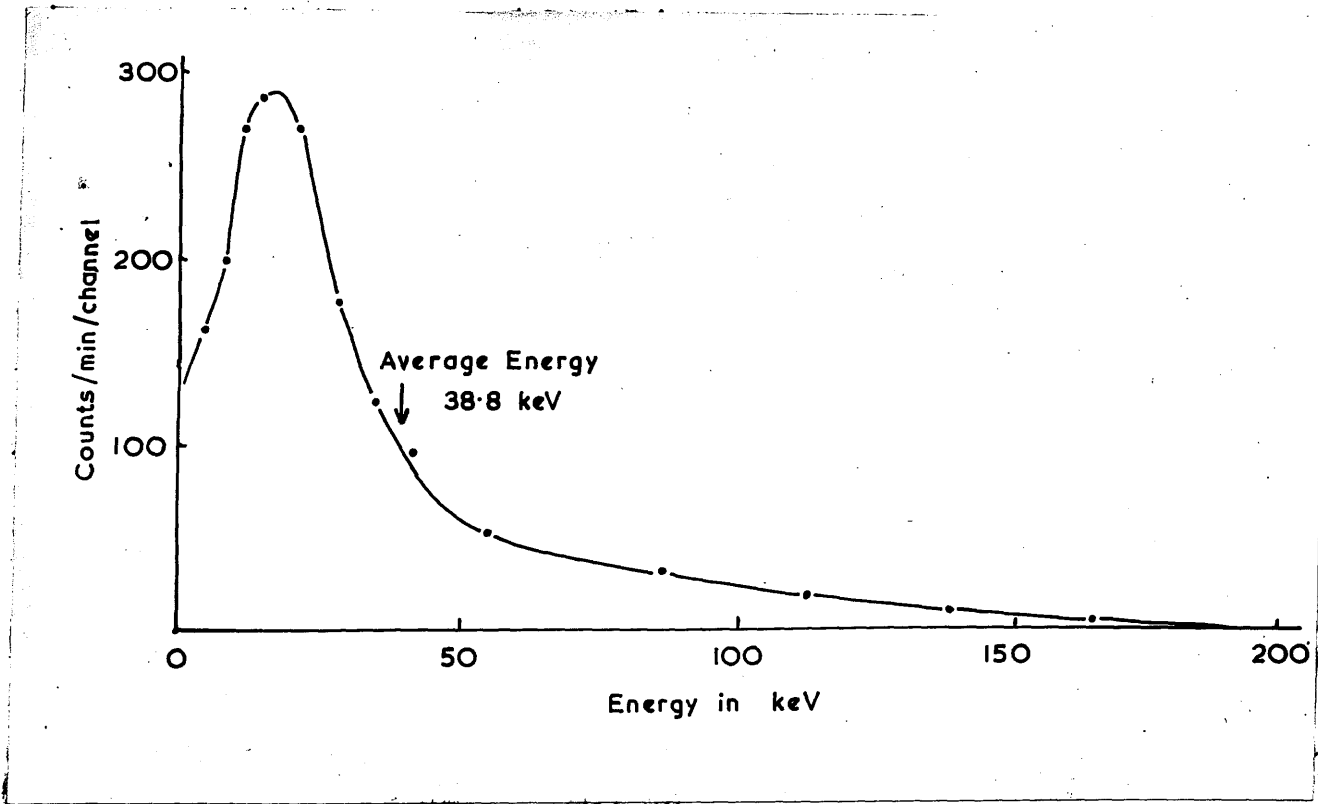
Fig. 19.

Natural background spectrum of ion chamber.

average energy of this spectrum was calculated and found to be
38·8 keV. Since the total counting rate was 2300 counts/min.
the background spectrum was equivalent to 32,800 counts/min. of
^{37}A. This is very small compared with the source strength
employed in an ionization current measurement ($\geqslant$ 5 x 10^6 counts/
min.), and represents an increase in the average energy $\sim \frac{1}{2}\%$.

The shapes of the K and L peaks were carefully examined
using a proportional counter filled with 60 cm. argon + 15 cm.
methane. The photographic method of recording and analysing the
pulse height distribution, described by Curran et al. (1949 a),
was used. This method, in which all the data required are
recorded in a few minutes, was found to be more accurate for the
detailed examination of peak shape than analysis by the single
channel pulse analyser. The K peak is symmetrical (fig. 20a)
and so the average energy of the K radiations is 2·82 keV., i.e.
the binding energy of the K electron in chlorine. As pointed out
by Pontecorvo (1950) the L peak consists of a mixture of L_I ,
L_{II} and L_{III} radiations, and so it is broad with a spread
towards high energies (fig. 20b). The contribution of L
radiations to $\bar{E}$ is small, however, so the use of the peak energy
of~200 eV should not lead to any appreciable error.

The ^{37}A was obtained by irradiation of spectroscopically
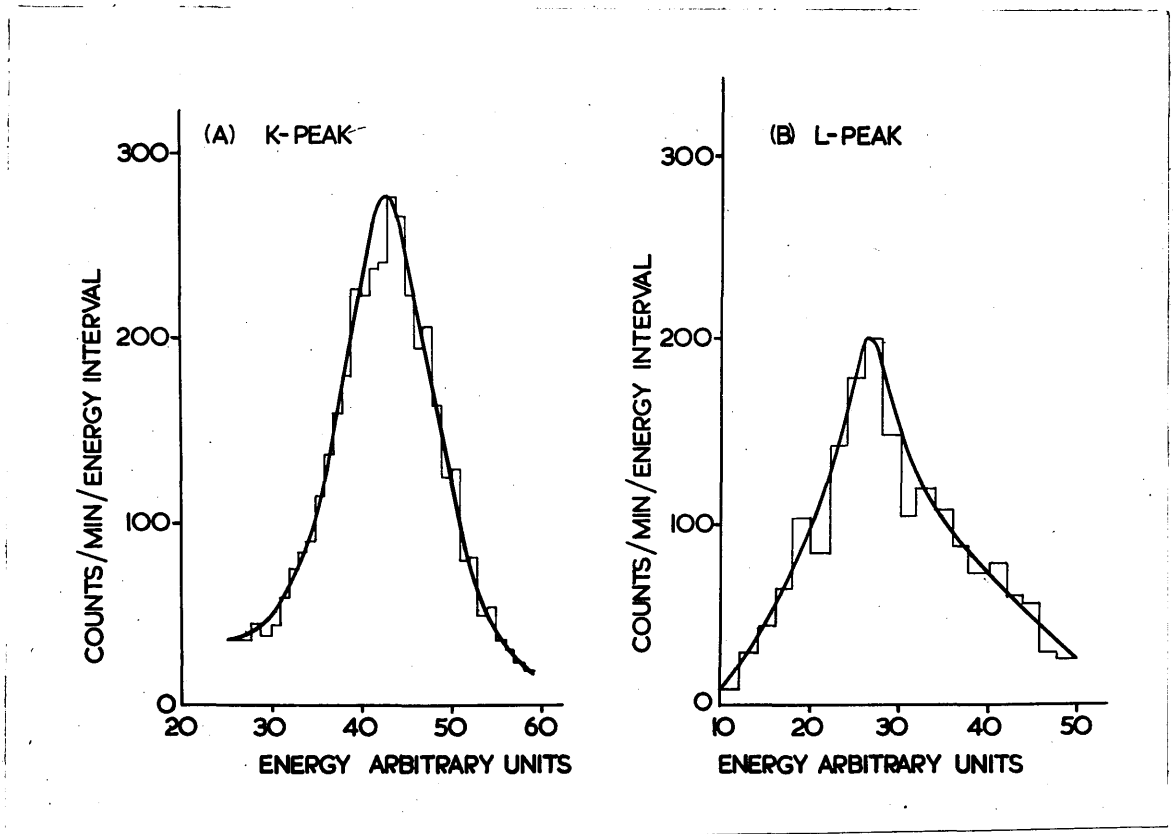pure argon in the Harwell pile. The only other radioactive
isotopes/

63.

Fig. 20.

K and L peaks from ^{37}A decay.

isotopes formed have very short half-lives and were allowed to decay until they were of negligible activity.

4.   Experimental Method.

(i) General

Although in principle V can be determined directly from equation (1), in practice an intermediate stage is required because the electrometer valve circuit used to detect the current i was not sufficiently sensitive to measure accurately the current caused by a count-rate $n \sim$ 50,000 counts/min.   It is difficult to measure very much higher count-rates with the required accuracy, and in order to use the optimum values for both i and n a factor $f \sim$ 1/100 between current and count-rate is required.   In the previous work this factor was obtained by measuring the current in an ion chamber and then bleeding off about 1% of it (measured by pressures or volumes) and by introducing this into an exactly similar vessel which was used as a proportional counter to determine n.
Hence,

$$f i = n e \overline{E}/V \tag{2}$$

The vessels used were very long (6 ft.) and of relatively small diameter ($1\frac{1}{4}$ in.).   It was assumed that, with the large ratio of length/diameter employed, the end-effect, even if it was not exactly/

exactly the same for counter and ion chamber, would not seriously affect the value of V obtained. A more accurate and direct method is available by employing field adjusting tubes in both ion chamber and counter. These tubes define the collecting or counting volumes precisely, and so the volumes can be calculated geometrically. The factor used was the ratio of the volumes of the counter and ion chamber, i.e. $k = 1/166$.

(ii) Absolute values of V.

Absolute values of V were determined for the gases argon, hydrogen, helium, and nitrogen using ^{37}A.

A quantity of ^{37}A sufficient to give an easily measurable current, together with the gas under observation, was used to fill the ionization chamber. This was then shared with the counter, and as the pressure in the chamber was high ($\sim$ 1 atm.) the sharing could be considered to give, with high accuracy, equal pressures in the two vessels.

The two measured quantities not hitherto considered in detail are the count-rate n and the current i .

Count-rate.

After the counter had been shared with the ionization chamber it contained, in addition to the ^{37}A, about 1 atm. of the gas under observation. In the case of argon, methane to a pressure of 20 cm. Hg. was added to give a suitable counting mixture./

mixture.   Long very flat plateaux similar to that shown
in fig. 21a were obtained.   The two parts of the plateau, K
radiations alone and K + L radiations, can be easily
distinguished.   This latter part, which gives the total number
of disintegrations, is the one required.   It was noted that
the escape of 2·62 KeV quanta does not affect the height of the
top part of the plateau, as they leave behind L quanta which will
be absorbed and detected in the counter when it contains argon.
With the other gases investigated (N_2 , He and H_2) it was found
that, although proportional tubes containing these gases could be
made to operate, better plateaux were obtained when $\sim$ 20 cm.
methane + 60 cm. argon were added.   Fig. 21 shows the plateaux
obtained with (b) ^{37}A + 1 atm. He, (c) this mixture + 19 cm.
methane + 1 atm. argon.   The higher total count-rate obtained
with (c) is due to the added argon trapping L quanta, which
escaped from the very transparent helium in case (b).   Since
the ion chamber is very much bigger than the proportional tube it
was assumed that the L quanta were trapped in the chamber even in
the case of helium, so that the count-rate from case (c) was the
one used in the evaluation of V.   After the plateau had been
plotted n was determined by using a voltage near the middle of
the plateau and counting several hundred thousand pulses.   The
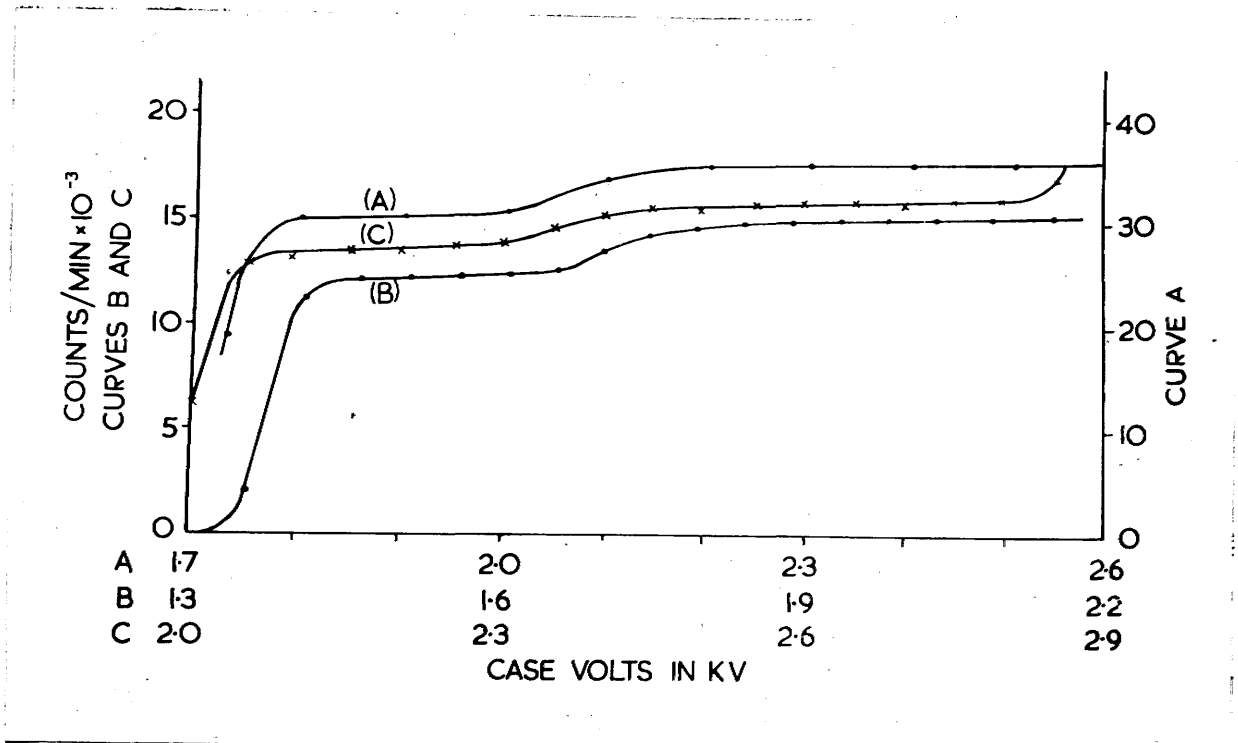count-rate/min. from this result was compared with the average
height/

Fig. 21.

Variation of count-rate with applied voltage.

(a) Plateau obtained with ^{37}A radiations in 20 cm. CH_4 + 1 atm. A.

(b) Plateau obtained with ^{37}A radiations in 1 atm. He.

(c) Plateau obtained after 19 cm. CH_4 + 1 atm. A had been added to mixture used in curve (b).

height of the plateau and a mean value adopted for n.

An experiment was carried out to check that no appreciable number of counts was being lost due to a counter dead-time. The counter was shared with a vessel of equal volume, and it was found that the count-rate remaining was, within the limits of accuracy of the experiment, exactly half the original count-rate.

Preliminary work was carried out to determine whether a Geiger or proportional counter was the more suitable for obtaining an accurate value for n. The values of count-rate obtained at a given applied voltage (on a plateau) were found to vary with the amplifier gain, the time constant of the input circuit of the amplifier and the type of scaler used. This was investigated and a procedure, which gave a consistent and accurate value for n, was adopted. An account of this preliminary work is contained in appendix II.

Current

When ^{37}A was used as a source of ionizing electrons relatively low pressures ($<$ 1 atm.) of even the transparent gases stopped practically all the electrons in the chamber and so no difficulty was encountered in obtaining saturation currents. A typical current-voltage characteristic is shown in fig. 22. It can be seen that saturation occurred with very low fields ($<$ 120 V on case). The saturation ion current was found to remain constant with no sign of gas multiplication taking place even with applied/
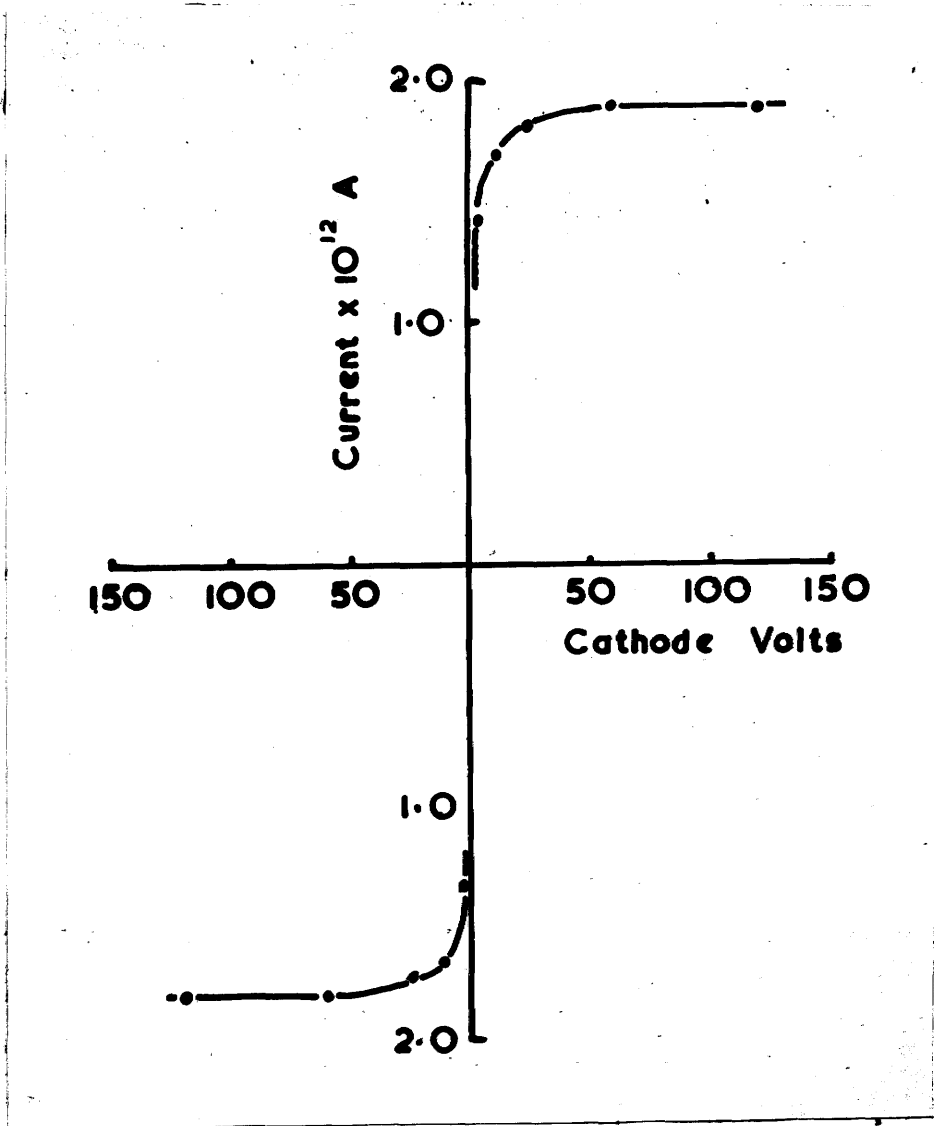
Fig. 22.

Current voltage characteristic.

applied voltages $\sim$ 2000 V.   The above results were found to
be true for all the gases investigated in this section.   Normally,
an applied voltage of 1050 V. was used.   The reason for using a
voltage much greater than the minimum required for saturation can
be seen from fig. 23.   Two curves are shown, giving the variation
in current with the voltage applied to the field tube.   It can be
seen that this voltage is not nearly so critical when the case
voltage is high.   The chambers were also found to be more stable
with high fields.

The values obtained from the absolute measurements are
listed below (in eV/ion pair) :

$$V_A = 27 \cdot 0 \; , \quad V_{He} = 32 \cdot 2 \; , \quad V_{H_2} = 37 \cdot 2 \; , \quad V_{N_2} = 35 \cdot 2 \; .$$

(iii)   <u>Relative values with ^{37}A.</u>

The absolute values for V in the various gases were checked
by measuring the ionization current produced in the gases relative
to that produced in argon as a reference gas.   This also gives
indirectly a check on V_A , as any consistent deviation between the
absolute and relative values of the gases helium, hydrogen and
nitrogen would indicate an incorrect value of V for argon.

The ion chamber was filled with an amount of ^{37}A sufficient
to give a measurable current together with $\sim \frac{1}{2}$ atm. of argon.
The saturation ion current was measured by a simplified method
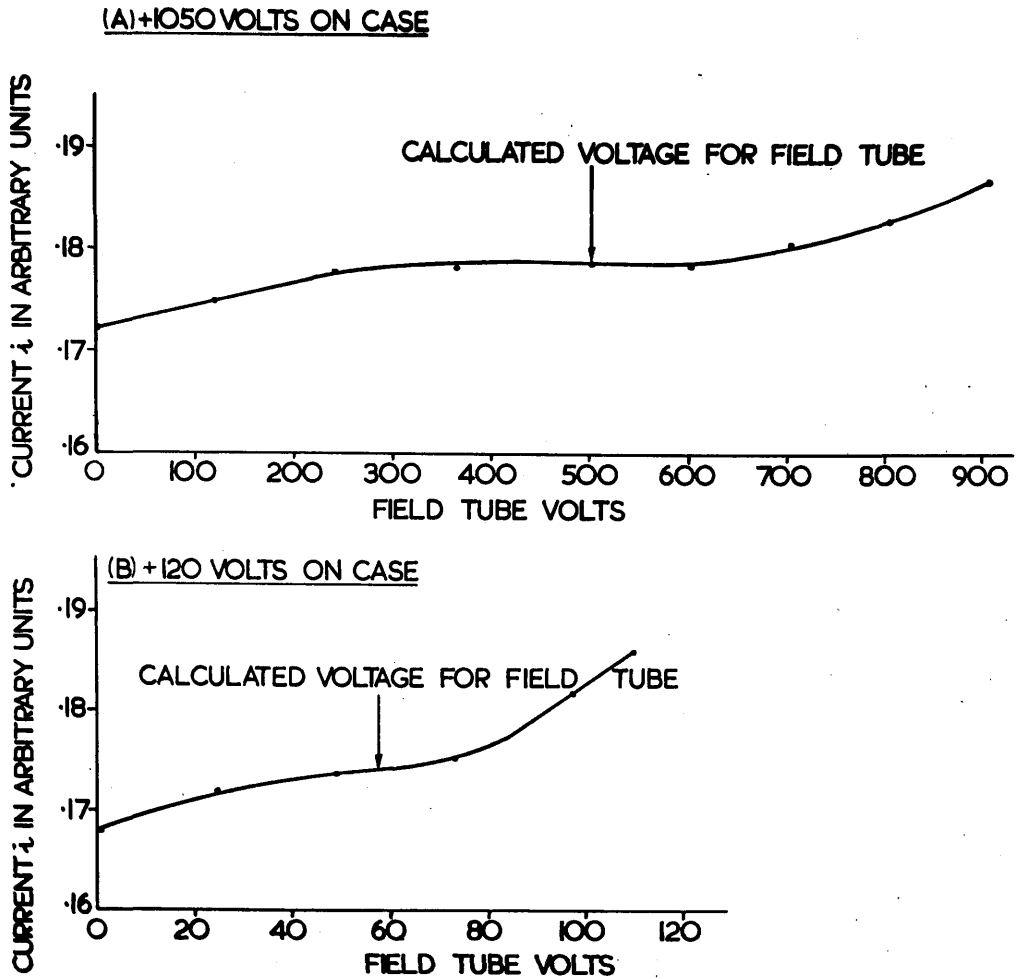since,/

71.

Fig. 23.

Variation of ion current with field tube volts.

since, for relative measurements, the meaning of the zero position in the current readings is not so important as in the absolute determinations.   In this case all ionization current measurements were made with only a positive case voltage of 1050V, and the bias voltage required to return the microammeter to its zero position was noted.   A check showed that, if the meter was carefully set to its zero position before taking each reading, the ratio obtained for two currents using this method was the same as that obtained with the "total swing" method used in the absolute measurements.   This simplified procedure enabled readings to be taken more rapidly and so reduced the corrections necessary to account for temperature fluctuations.

After the ionization current had been measured with only argon in the chamber 5 cm. of the other gas was added and the current remeasured.   This procedure was continued until the total pressure was $\sim$ 2 atm., and the variation of current with percentage argon, from 100 to $\sim$ 30% argon, was plotted.   The experiment was repeated starting with $\sim \frac{1}{2}$ atm. of the other gas and adding argon so that a similar curve from 0 to $\sim$ 70% argon was obtained.   These two curves were fitted at 50% argon and the experimental points were found to lie on a smooth curve. A $-$ He , A $-$ H$_2$ and A $-$ N$_2$ mixture curves are shown in fig. 24 a, b, c.   From these curves the following values of V for helium, hydrogen and nitrogen relative to V_A = 27·0 eV. were calculated (in eV/ion pair)
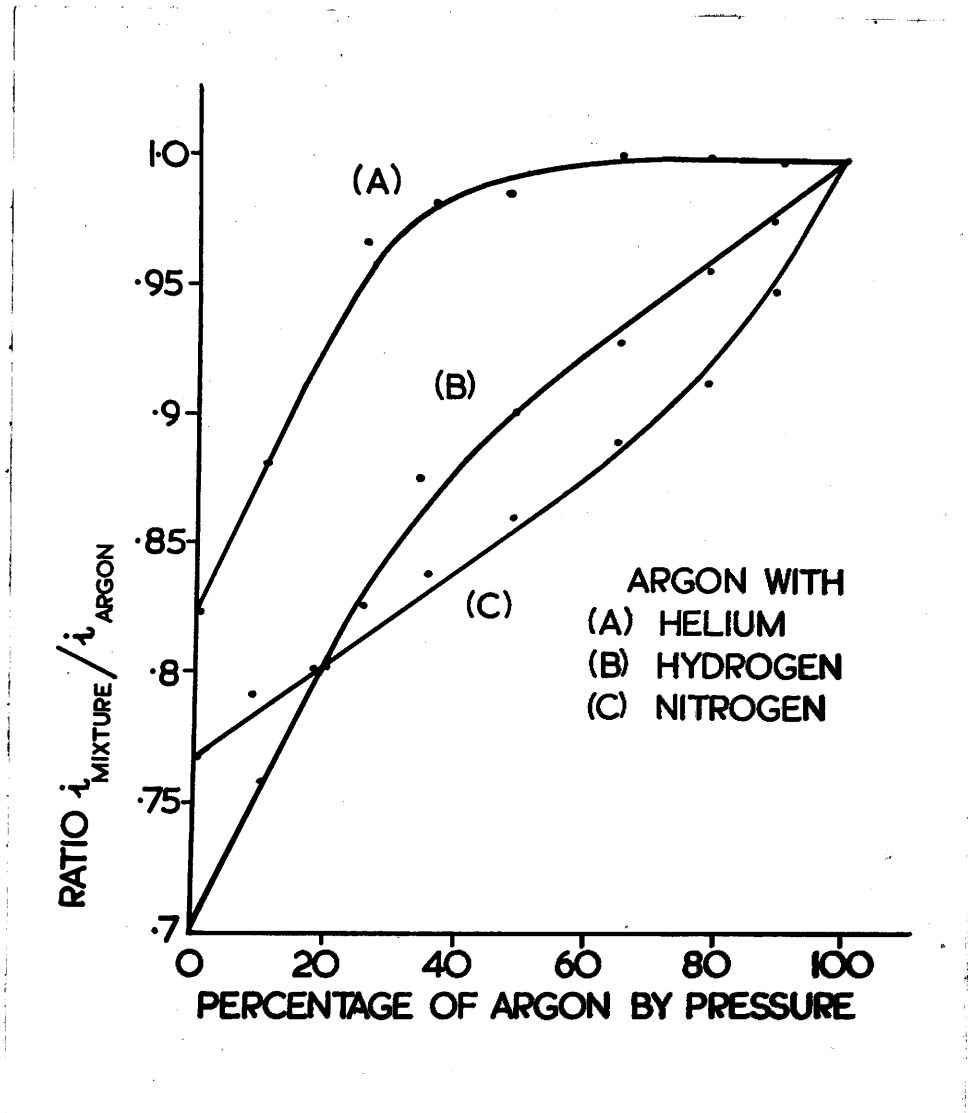
V_{He} /

Fig. 24.

Ratio of ion currents in gas mixtures (^{37}A).

$$V_{He} = 33 \cdot 0 \ , \ V_{H_2} = 38 \cdot 4 \ , \ V_{N_2} = 35 \cdot 4 \ .$$

(iv) <u>Relative values with tritium.</u>

Using tritium as a source of ionizing electrons relative values of V for several gases were determined. A more accurate method of plotting the ion current – gas mixture curves, without the necessity of curve fitting, was adopted. Another ion chamber identical to the first, was used. Both ion chambers were evacuated and a suitable amount of tritium was added to one together with about 3 cm. of methane. After the gas had attained equilibrium pressure in the first chamber it was shared with the second chamber. By measuring the ion current in each, the sharing process was checked. One chamber was filled with argon to a pressure of 1 atm. and the other with the gas under observation. The pressure of this gas depended on its stopping power for electrons and in the case of hydrogen, 6 atm. were required to stop nearly all the tritium β –rays in the chamber. When a high pressure was used a check was made to ensure that saturation in the ion current had been obtained. The ratio of the saturation ion currents in the two chambers gave directly the value of V. Sufficient tritium was available to repeat the measurements in each case. The ion current – gas mixture curves are plotted and can be seen from figure 25 a, b, c, d to be similar in shape to those obtained using ^{37}A. Again the values of V for the gases investigated/
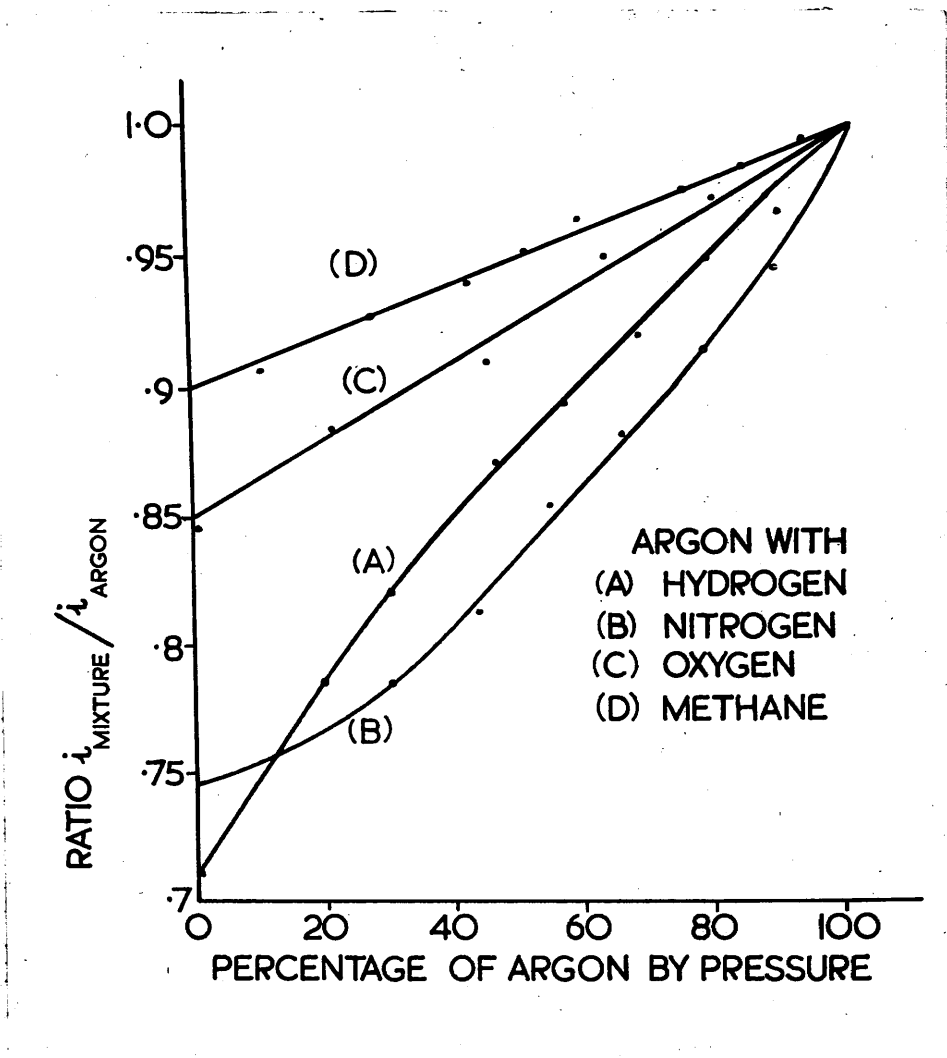
Fig. 25.

Ratio of ion currents in gas mixtures (tritium).

investigated, relative to $V_A = 27 \cdot 0$ eV/ion pair are listed :

$$V_{H_2} = 38 \cdot 0 \ , \ V_{N_2} = 36 \cdot 0 \ , \ V_{air} = 35 \cdot 0 \ , \ V_{O_2} = 32 \cdot 2 \ , \ V_{CH_4} = 29 \cdot 5 \ .$$

In the course of the work it was also checked that there was no detectable variation of V with pressure in a single gas.

5.   Purity of Gases.

No special precautions were taken to purify the gases; in general commercial qualities were used.   Details of their purities are listed below.

Argon:- A, $99 \cdot 8\%$; N_2, $0 \cdot 2\%$;   traces of O_2, CO_2, CO, H_2O.

Helium:- He, 100% ;   traces of CO_2, O_2 and   other carbonaceous matter as CO_2 .

Hydrogen:- H_2, $99 \cdot 8\%$; O_2, $0 \cdot 9\%$; N_2 $0 \cdot 11\%$.

Nitrogen:- N_2, $99 \cdot 8\%$; O_2, $0 \cdot 2\%$.

Oxygen:- O_2, $99 \cdot 6\%$;   A, $0 \cdot 4\%$.

Methane:- CH_4, $90 \cdot 5\%$; CO_2, $0 \cdot 17\%$; O_2, $0 \cdot 05\%$;   CO, $0 \cdot 51\%$; C_2H_6, $2 \cdot 25\%$; N_2, $6 \cdot 52\%$.

In addition to the above, 1 to 2 cm. of methane were added to an atmosphere of the gas under observation to give added stability.
With/

With the exception of methane, the gases used thus contained

~ 2% impurity.   In the case of methane the value quoted for

V has been corrected to allow for the 6·52% nitrogen impurity.

6.   Discussion of Results.

 (i) General.

There was no significant difference in the values of V

obtained by the three different methods, viz. absolute and

relative values with ^{37}A and relative values with tritium.

Column 2 in table V gives the best values of V from a

consideration of all the results obtained.   An estimate of

accuracy is difficult to obtain, but it is probably safe to claim

that the values of V are correct to $\pm$ 0·5 eV.

Table V.

Gas	Electrons		340 MeV. protons	P$_0$ ⍺ –particles
	V in eV	Vgas/VA	Vgas/VA	Vgas/VA .
A	27·0	1·00	1·00	1·00
He	32·5	1·20	1·17	-----
H$_2$	38·0	1·41	1·38	1·27
N$_2$	35·8	1·32	1·31	1·31
air	35·0	1.29	1·30	1·26
O$_2$	32·2	1·19	1·23	1·12
CH$_4$	29·5	1.09	-----	1·07

(ii)/

(ii)   Absolute Values.

The value V_A = 27·0 eV/ion pair is low compared with the previous value of 28·5 $\overset{+}{-}$ 0·5 eV. obtained by this method (Curran et. al. 1950).   It is possible that this latter value is spuriously high due to insufficient correction being made for "end-effect".   A value of 28·4 was also obtained by Gaertner (1935) for argon and a lower value of V_A = 26·0 eV. by Gerbes (1937).   On the other hand the most recent value obtained for argon, i.e. 26·9 eV. for electrons of energy 17·4 keV. (Nicodemus, 1946) is in good agreement with the present work.

The values of V_{O_2} = 31·6 eV , V_{CH_4} = 29·8 eV. obtained by Gaertner (1935) are also in close agreement with the present work.   Gerbes (1937) obtained the value V_{O_2} = 30·0 eV.;   it is interesting to note that the values obtained by Gerbes, for the gases common to the two experiments, are lower than those obtained by the author by a roughly constant amount (4 – 6%).

The results for helium and hydrogen are close to those obtained by Lehmann (1927) who gives V_{He} = 31 eV. and V_{H_2} = 37 eV. for electrons of energy 400 eV. to 1 keV.

As far as the absolute values are concerned, most information is available for comparison in the cases of air and nitrogen.   The figure of 35·0 eV. for air is high compared with several/

several previous values for electrons, viz.

    (i) 31·0 eV. (Curran et. al. 1950).

As pointed out in that paper, this value is suspect due to a possible error in the sharing process.

    (ii) 31·6 eV. for 9 - 59 keV. electrons (Eisl 1929).

    (iii) 32·8 eV. for 10 - 40 keV. electrons (Gerbes 1937).

In agreement with the present work Gaertner (1935) found the values V_{N_2} = 35·8 eV., Vair = 35·2 eV. Breunig (1936) also obtained a higher value for nitrogen, viz. 34·0 eV.

(iii) Relative Values.

    Column 3 in table V gives the value of the ratio Vgas/Vargon. This is useful for the purposes of comparison as these relative figures are probably more accurate than the absolute values of V, since only readings of the ionization current are involved. A recent study of the average energy expenditure per ion pair for 340 MeV. protons has been made by Bakker & Segré (1951). Their results for the ratio Vgas/Vargon are shown in column 4, table V, and are seen to be the same to within 2 or 3% as obtained in the present work with electrons. The method consisted of allowing the proton beam to cross two identical ionization chambers. One was filled with argon at atmospheric pressure and served as a monitor; the other was successively filled with the gases to be investigated. Corrections were made for differences in temperature and filling pressure/

pressure, and saturation in the current measurement was checked in every case. V was then calculated in the following way,

$$V = \frac{-dE}{dN} = \frac{-dE}{dx} \Big/ \frac{dN}{dx}$$

Values of the term $\frac{-dE}{dx}$ were obtained for each gas from theoretical tables (unpublished) and since $\frac{dN}{dx}$ was proportional to the ionization measured in the chamber, values of V relative to argon could be calculated. To convert these relative values to absolute values a measurement (by Chamberlain, Segré & Wiegand, unpublished) of the number of ion pairs produced by one 340 MeV. proton crossing 1 cm. of argon at atmospheric pressure and 0°C was used to give $\frac{dN}{dx}$ absolutely for argon. This, together with the theoretical value of $\frac{-dE}{dx}$ gave $V_A = 25 \cdot 5$ eV/ion pair. Thus the absolute values of V obtained are $\sim 6\%$ lower than those in column 1, table V.

There are no data for α-particles which can be used for a direct comparison, as most of the work has used air as the standard gas. The value of Vair for the present work with electrons is almost exactly the same as that obtained using α-particles, Vair $= 35 \cdot 1$ eV. for RaC' α-particles (Gray 1944) and $V_{N_2} = 36 \cdot 3 \overset{+}{-} 0 \cdot 4$ eV, Vair $= 34 \cdot 7 \overset{+}{-} 0 \cdot 5$ eV. for Po α-particles (Alder, Huber & Metzger 1947), so that the relative values, for Po α-particles/

particles, of two recent observers (Stetter 1943; and Dick, Falk-Vairant & Rossel 1947) were recalculated in the form Vgas/ Vargon. These values are listed in the final column in table V. Although the agreement is not so striking as in the proton case it is, nevertheless, fairly good. It would have been possible to obtain better agreement by selecting results for individual gases given by earlier workers, as there is a fairly large variation in the α -particle values cited in the literature.

The ionization-gas mixture curves are further discussed, in conjunction with similar curves obtained for α -particles, in chapter VI.

7.   General Conclusions.

As stated above, it is considered that the numerical results given for electrons in table V are correct to $\overset{+}{-}$ 2%. It should be noted that the accuracy of the results obtained has depended largely on the recent improvements in the form of proportional counters (Cockroft & Curran,1951) and it appears unlikely that any appreciably large sources of error remain in the method.

A continuation of the work is suggested by the similarity in the relative values for electrons and protons. It has been shown that values for α -particles of high energy may also be in rather close agreement. These considerations led to the present method/

method being used to obtain more precise results for the ionization of Po α-particles in the gases previously investigated for electrons.   Chapter VI contains the results of this work.

Chapter V

Variation of V_A and V_{N_2} with E.

In chapter II it was noted that Pigge (1934) found a large increase of V_{N_2} with decreasing energy for electron energies between 0·3 and 3 keV. in contrast to the results of Freund (1935) and Breunig (1936) who found a constant value for Vair between 100 and 300 eV. It was realized that ^{37}A afforded an opportunity of studying the variation of V with ionizing energy down to ~ 200 eV. without the difficulty, encountered by Pigge, of introducing a beam of slow electrons into a gas filled ionization chamber.

Kirkwood et al. (1948) and Pontecorvo (1950) have described the method which consists of using a proportional counter to observe the distance (on an energy scale) between the K and L peaks produced by the ^{37}A decay. For an argon + methane mixture Pontecorvo (1950) stated that their results showed that V, for electrons of 200 to 300 eV., was at most 20% greater than V for 2·82 keV. electrons. This result was used by Pontecorvo in the following way. "The upper limit for V in a mixture of argon + methane combined with the statement of Curran et al. (1949a) on the increase of V in methane proves that, at least in argon or xenon, V is constant down to the lowest energies." Curran et al. actually stated that V_{CH_4} increased with increasing energy; in a footnote Pontecorvo assumes this to be a misprint and uses the converse statement/

statement.   Since this was not a misprint the reasoning given
by Pontecorvo is not valid.   The magnitude of this effect was not
stated by Curran et al.;   it was in fact very small and subsequent
work has shown that the effect was probably spurious.   In view
of this criticism and since more precise results are obtainable by
using "end-effect free" counters the problem was reinvestigated.

A proportional counter was filled with a small quantity of
$^{37}A + \sim 5$ cm. methane + 1 atm. argon.   A peak corresponding to
the decay by K-capture was found, and then the amplifier gain
increased by a factor of 4 and the L peak observed.   This peak is
complex being a mixture of L_I , L_{II} and L_{III} radiations ;   the
contributions of the different radiations to the composite peak may
be evaluated as follows.   (a)   After capture of an L electron an
electron or quantum will be radiated.   From fig. 26 (constructed
from tables of Landhold-Börnstein, 1950) it can be seen that the K
and L_I electrons are in S states while the L_{II} and L_{III} electrons
are in P states.   Since the P wave is zero at the nucleus the
number of captures from L_{II} and L_{III} levels will be negligible
compared with the number of captures from the L_I level.   If we
consider a total of 100 transitions 7·5 are by L_I capture, (Rose &
Jackson, 1949).   (b)   If a Kα photon escapes from the atom a hole
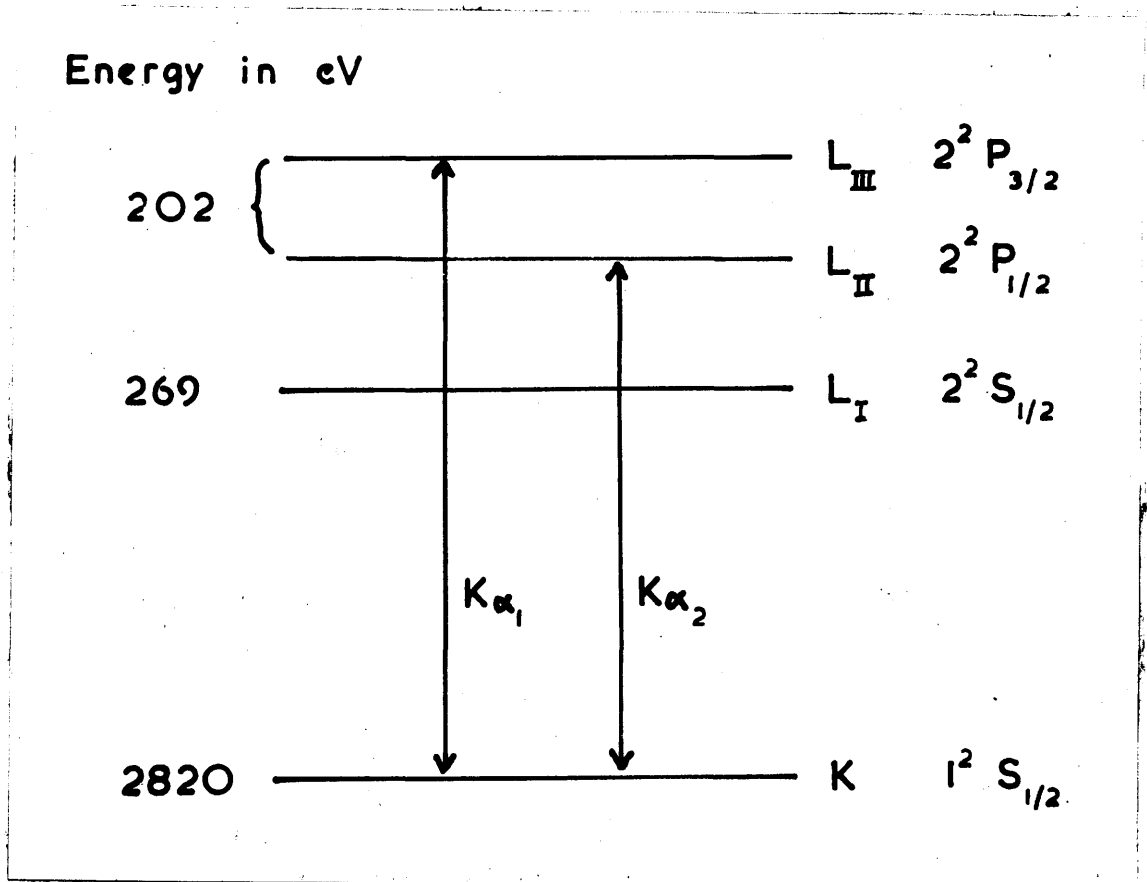will be left in an L_{II} or L_{III} level.   This will finally be
detected/

Fig. 26.

Energy level diagram for chlorine.

detected as an L radiation.   Since the Auger effect is 94% then out of 100 transitions the total number of K quanta which escape and hence of L_I or L_{II} electrons (or quanta) emitted will be 92·5 x 0·06 = 5·55.   Thus the weighted mean of the energy of the L radiations is (7·5 x 269 + 5·55 x 202) / (7.5 + 5·55) = 240 eV.

The composite L peak obtained by experiment is shown in fig. 27 and the centre of gravity of the distribution is indicated. This should coincide with the energy of 240 eV. extrapolated from the position of the K peak if V_A is constant.   In practice there is a small difference between the two points.   Were this difference interpreted literally it would mean that V_A was ~ 5% **less** at 240 eV. than at 2·82 keV.   Since this is unlikely it can be stated that V_A is constant within the limits of accuracy of the experiment.   Although the accuracy did not appear to justify a thorough analysis it can be seen that the shape of the L peak is compatible with two radiations of comparable intensity at 202 and 269 eV.   In a separate experiment the amplifier gain factor was determined directly by observing the peak from the fluorescent x-rays of copper at low and high gains.   The variation of V_A with energy was not investigated for the higher energy range since the work of Curran et al. (1949a) and Pontecorvo (1950) has shown that V_A is constant, to within narrow limits, ~ 2%, in the range 2·82 to ~ 40 keV.

Due/

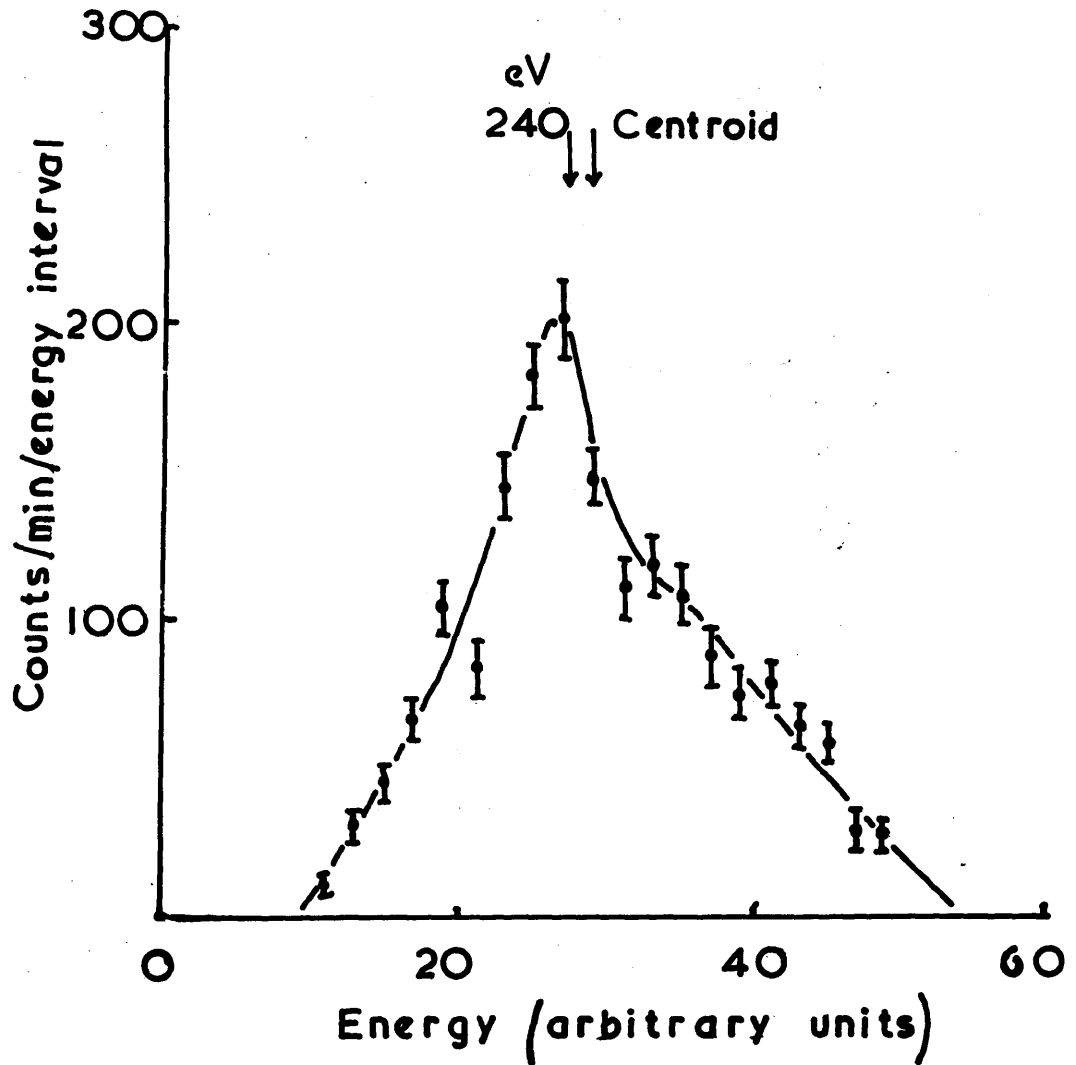**Fig. 27.**

L peak from ^{37}A decay.

Due to the difficulty of investigating the variation of V absolutely by means of the K and L peaks of ^{37}A the variation of V_{N_2} was examined by a comparative study assuming V_A to be constant. Using ∼ 5 cm. methane + 1 atm. nitrogen (from which all traces of oxygen had been removed) as a filling gas in a proportional counter the K and L peaks were observed as before. The ratio, position of K peak/position of L peak, for argon was found to be very nearly equal to that for nitrogen. To extend the energy range of the observations the whole experiment was repeated to compare the position of the 46·5 keV. Y peak from Ra D with the 2·82 keV. K peak from ^{37}A. (The most recent measurement of the Y -ray energy is due to Ewan & Ross, 1952). Owing to the difficulty in deciding the exact position of the maxima of the distributions in nitrogen, there is a slight uncertainty in the final result, but it can be stated that V_{N_2} does not increase by more than 5% for the energy range 46·5 to 2·82 keV. Further, it can be stated that there is not more than 5% increase in V_{N_2} between 2·82 keV. and 240 eV. This gives a possible variation of 10% between 0·24 and 46·5 keV. It is thought that V does not vary by nearly as much as this, but, due to the previously discussed uncertainty in the position of the peaks, this upper limit for the variation cannot be reduced. The low energy experiment was repeated using a counter filling of methane alone and it was checked that, within the limits discussed above/

above, V_{CH_4} was constant between 2·82 and 0.24 keV.   This means that the small amount of methane admixed with the argon or nitrogen does not affect the final conclusions.

The result for nitrogen is in good agreement with the curve obtained by Curran et al. (1949a).   It is also in agreement with the work of Eisl (1929) (as modified by Gerbes, 1935) for electrons of energies between 10 and 60 keV.   For low energies the present work is compatible with the results of Freund (1935) and Breunig (1936) but is in marked contrast to the results obtained by Pigge (1934).   The empirical formula, $V = 31\cdot62 + 5\cdot27/\sqrt{(E - E_i)}$ eV. deduced by Gerbes (1935) on the basis of Pigge's results leads to a value of V_{N_2} ∼ 20% higher at 240 eV. than at 2·82 keV.   The present work, together with the criticism of Pigge's results given in chapter II, means that the above formula of Gerbes cannot be considered to represent the variation of V with E in nitrogen or air.

Chapter VI

Energy per Ion Pair for Polonium α-particles.

1. Introduction.

In chapter IV the close agreement between the ratios Vgas/Vargon for slow electrons and for very energetic (340 MeV.) protons was noted. In view of this agreement, and since sufficient data for a similar comparison in the case of α-particles was not available it was decided to investigate the ionization of the same gases by Po α-particles. The method, employed in the case of electrons, of using end corrected cylinders as proportional counters and ionization chambers is immediately applicable to α-particles.

2. Apparatus.

An ionization chamber, capable of withstanding pressures in excess of 6 atm., and fitted with terminals, as shown in fig. 11, p.45 was constructed. The distance between the ends of the field adjusting tubes was ~40 cm. and the cylinder had an inside diameter of 14 cm. The central electrode was a tungsten wire 0·02 cm. in diameter. This wire diameter was chosen so that the vessel could be used either as an ionization chamber or, by increasing the applied voltage until gas multiplication started, a proportional counter. The source was mounted on a probe running parallel to the central wire and maintained at a voltage corresponding to its position in the field. It was arranged so that the source was situated/

situated approximately midway between the ends of the chamber and also half way between the central wire and the case. The minimum distance of the source from any part of the chamber wall was 6 cm. and care was taken to ensure that the pressure of the gas under observation was great enough to make the range of Po α -particles less than 6 cm.

The electrometer valve circuit described in chapter IV, section 2, was used to measure the ionization current.

3. The polonium source.

The source was made by dipping a thick silver foil (area $\sim \frac{1}{2}$ cm.^{2}) into a solution of Radium D + E + F in hydrochloric acid. The back of the foil was covered with "Glyptol" sealing paint so that all the α -particles were emitted towards the central wire. The energy distribution of the α -particles was examined by using the chamber as a proportional counter and the curve obtained is shown in fig. 28. It can be seen that the peak is symmetrical except for a slight preponderance of low energy particles making the average energy of the pulse distribution 97% of the peak energy. (A peak energy of 5·303 MeV., as determined by Chang 1946, was used). There are probably two causes for this energy loss, (a) finite thickness of the source, and (b) excitation of metastable states in argon. This energy would be lost/
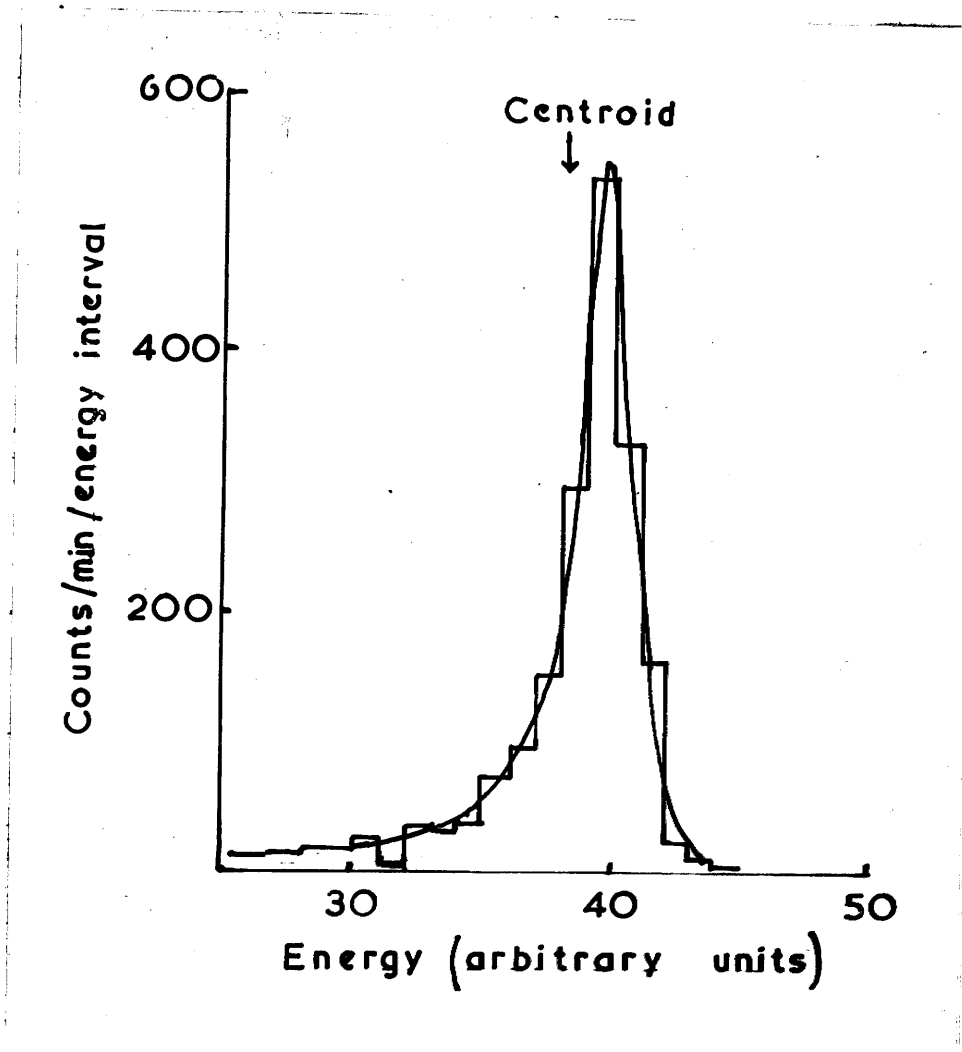
Fig. 28.

Energy distribution of Po α-particles.

lost in a proportional counter pulse but detected in ion chamber operation.   We deduce that the energy of the particles, so far as it affects the ionization current, may be between 97 and 100 % of its known value and we adopt 98.5% as the most probable value.

4. Absolute value of V for argon.

(i) General.

In chapter IV the following equation was derived for the evaluation of V,

$$i = ne \overline{E}/V \tag{1}$$

In the case of slow electrons a factor was required between the current and the count-rate.   With Po α-particles, however, sufficient energy is dissipated in the ionization chamber to give a measureable current, $\sim 10^{-12}$A, if the source strength is $\sim 10,000$ counts/min.   This is also an optimum value for the measurement of n and so it was not necessary to divide the source.   To obtain an absolute value of V for argon, i was measured using a filling of 1 atm. argon + 1 cm. methane.   Then ~ 10 cm. methane was added and the voltage increased until the chamber was operating as a proportional counter with gas multiplication.   From a count rate – applied voltage curve the value of n was deduced.   Equation (1) was then used to calculate V.

(ii) Current measurement.

The/

The measurement of the saturation ion current was complicated by a difficulty, due to the low counting rate of the source, not encountered in the previous experiments with electrons.

The standard deviation of a counting rate $\sim 10,000/\text{min.}$ is $\sim 100/\text{min.}$ or about $\pm 1\%$. This means that in the current measurement the deflection of the microammeter will fluctuate about a mean position with a maximum amplitude of $\sim 2 - 3\%$. The fluctuations will be random with a frequency $\sim 2/\text{sec.}$ This is consistent with actual observations. The technique used in the current measurements has been previously discussed and required the setting of the microammeter to a known position by means of a biassing voltage. This process was made rather difficult by the fluctuations. It was recognized that in order to reduce the random variations to a negligible amplitude (say $\lesssim 0.1\%$), a source strength $\sim 10^6$ counts/min. would be required. Such a source would necessitate an accurately measured fraction $\sim 1\%$ being used for the determination of n. It was considered impracticable to make such a division of a solid source, with the required accuracy. In order to avoid the necessity of dividing the source a count rate $\sim 15,000/\text{min.}$ was used and electrical methods of damping the current measuring system were considered.

For effective damping of fluctuations $\sim 2/\text{sec.}$ the time constant of the system must be made long compared with a second, say/

say 5 - 10 sec.   With the existing apparatus this could be
achieved in two ways.

(a)   A condenser of capacity 50 - 100 $\mu\mu$ F could be connected
across the grid leak Rg which had a resistance $\sim 10^{11} \Omega$.   The
resistance of this condenser would have to be high compared with
$10^{11} \Omega$;   a resistance of more than $10^{13} \Omega$ would be required.
It appeared that a parallel plate condenser was the best type for
satisfying the stringent leakage resistance requirements and also
having the required capacity.   Such a condenser would have to be
housed in the box containing Rg ;   this limited the area available
for the plates to ~ 25 cm.^{2} which meant a plate separation of
< 0.5 mm.   A condenser with the above dimensions and having a
resistance $> 10^{13} \Omega$ would be very difficult to construct and so,
unless the apparatus were redesigned, this solution did not appear
to be practicable.

(b)   The other method of damping, and the one which was adopted
in practice, consisted of connecting a condenser across the
microammeter itself.   Since the resistance of the meter was
$\sim 1000 \Omega$ a condenser of capacity 10,000 μ F was required to
give a time constant ~ 10 sec.   Five electrolytic condensers each
of 2000 μ F (12 V working) were connected in parallel across the
meter.   This produced adequate damping but the setting of the
bias/

bias voltage was made more laborious since the charge on the condenser had to be altered when the voltage was changed; this meant that a final reading could not be taken for some time after an adjustment of the bias voltage. From this point of view as small a capacity as possible should be used. In practice 8000μF. was found to be the optimum value for the condenser.

To compare the results obtained with and without damping the following experiment was carried out. With the meter undamped a current reading was taken, allowing 2 min. for resetting the microammeter to the zero position. This was repeated ten times and the results are shown in table VI.

<u>Table VI.</u>

Bias Volts.	Temp. °C.	Bias Volts.	Temp. °C.
0·751	19·5	0·734	19·7
0·749	19·5	0·746	19·7
0·734	19·6	0·742	19·9
0·741	19·6	0·738	20·0
0·737	19·6	0·746	20·0

Mean = 0·742 V at 19·7°C.

With an 8000 μ F. condenser across the meter several readings were taken each occupying about 3 min. The readings were found to be nearly/

nearly identical and they did not differ significantly from the mean value given above.   From this experiment it was deduced that no appreciable error would be incurred by using the damped meter and taking a single reading.   The time taken per reading is important when plotting mixture curves in the relative measurements.

Saturation characteristics were plotted for argon at pressures of 1 atm. and 2 atm. (in each case ~ 1 cm. methane was added).   These curves are shown in fig. 29.   Although multiplication can be seen to have started with a case voltage of — 1000 V., it was found that there was still no sign of multiplication taking place with an applied voltage of + 2000V. The slight difference in the saturation currents in the two cases was due to a temperature change.

In the electron experiments a "total swing" method of measuring the current was used to eliminate the possibility of a zero error.   In this case it was found more convenient to measure the biassing voltages required to return the microammeter to zero first with a positive and then negative applied voltage.   A typical set of readings is given in table VII.

Fig. /
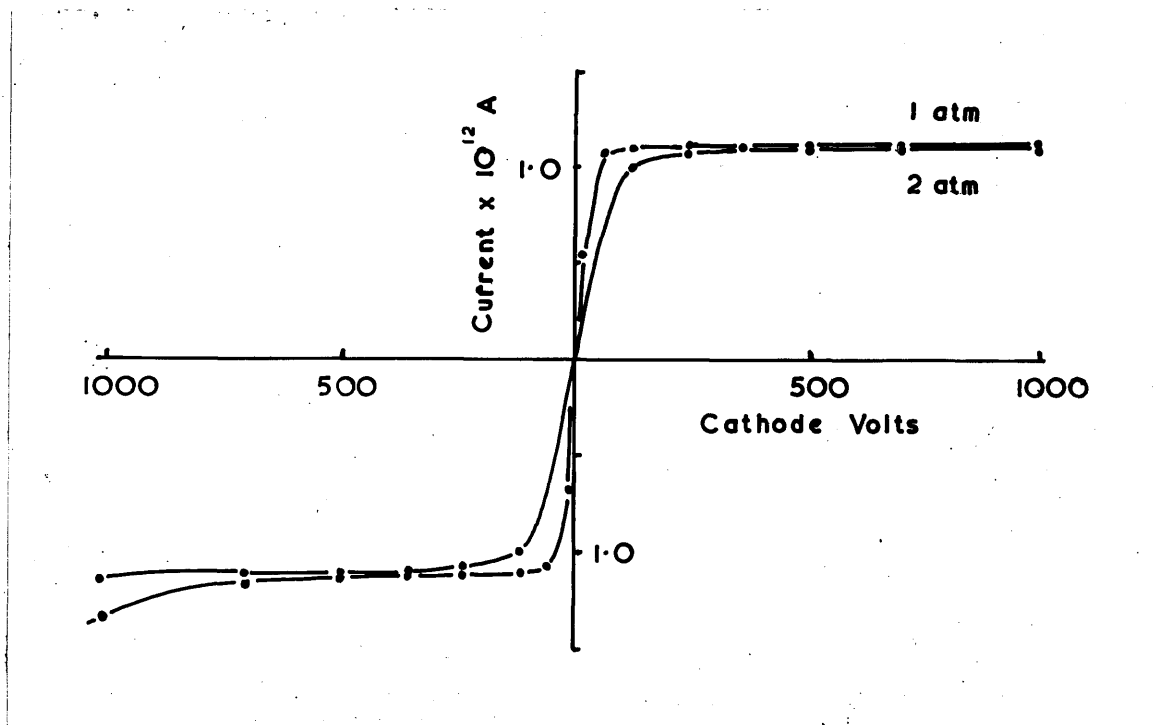
Fig. 29.

Current − voltage characteristic for Po α − particles
in argon.

Table VII.

Applied Volts.	Biassing Voltage		Temperature $^{\circ}$C.	
+ 500	1·103			20·7
"	1·095			20·8
"	1·097	Mean =	Mean =	20·8
+ 360	1·105	1·098	20·9	20·9
"	1·097			21·0
"	1·090			21·1
− 500	1·090			21·1
"	1·093			21·1
"	1·102	Mean = 1·097		21·2
− 360	1·090		Mean = 21·25	21·3
"	1·102			21·3
"	1·083			21·4

The most probable errors of the mean values quoted are $\sim$ 0·3 %.
Reducing each group to refer to a temperature of 21·1°C. the mean
value of the whole set is found to be 1·098.   Even with the random
fluctuations it is considered that the final value for the current
reading/

reading is not in error by as much as 1%.

(iii) <u>Count rate.</u>

The chamber was operated as a proportional counter and a count rate - applied voltage curve was plotted. A long flat plateau was obtained and an accurate value for n was found by counting ~100,000 pulses at a voltage corresponding to the middle of the flat portion of the curve.

A ratio of n/i was obtained from the above measurements. After four months the source had decayed to approximately half its original strength and the ratio was remeasured. The two values were found to agree to within 2% and a mean value was adopted. After the absolute value of Rg had been redetermined by the electrometer valve method the final value for V_A was found to be,

$$V_A = 25 \cdot 9 \overset{+}{-} 0 \cdot 5 \text{ eV/ion pair.}$$

5. <u>Relative Values.</u>

The measurement of relative values was simplified by the solid nature of the polonium source. The chamber was fitted with the gas under observation, at a sufficient pressure to make the α -particle range < 6 cm., and the saturation ion current measured. After the chamber had been evacuated and refilled with argon the current was again measured. The ratio of the two currents gave directly V_{gas}/V_A. After three months the source had decayed to ~60% of its original strength and the ratio was again determined. When practicable/

practicable ion current - gas mixture curves were plotted and used to reduce the possibility of error in the relative values. In the α-particle experiments difficulty was encountered, in certain gases, in obtaining saturation in the ionization current with the maximum available voltage of 2000 V. For this reason it was not always possible to plot mixture curves; the gases will be discussed individually.

(i) Nitrogen.

A characteristic curve for nitrogen was plotted and it was found to be identical in shape to the argon curve shown in fig. 29. Saturation ion currents were obtained for applied voltages from + 240 V. to + 2000 V. The ratio V_{N_2}/V_A = 1.39 was obtained for both values of the source strength.

(ii) Air.

By plotting a characteristic for ionization current in air at 1 atm. it was observed that saturation might not have been obtained with 2000 V. The minimum pressure of air needed to stop all the α-particles in the gas was calculated to be 48 cm. Curves were drawn of current against pressure of air from 50 to 150 cm. for applied voltages of + 1000 V. and + 2000 V. These are shown in fig. 30 and it can be seen that a saturation ion current was obtained at the lowest pressures. A mixture curve for air-argon was not plotted because of the difficulty in obtaining/
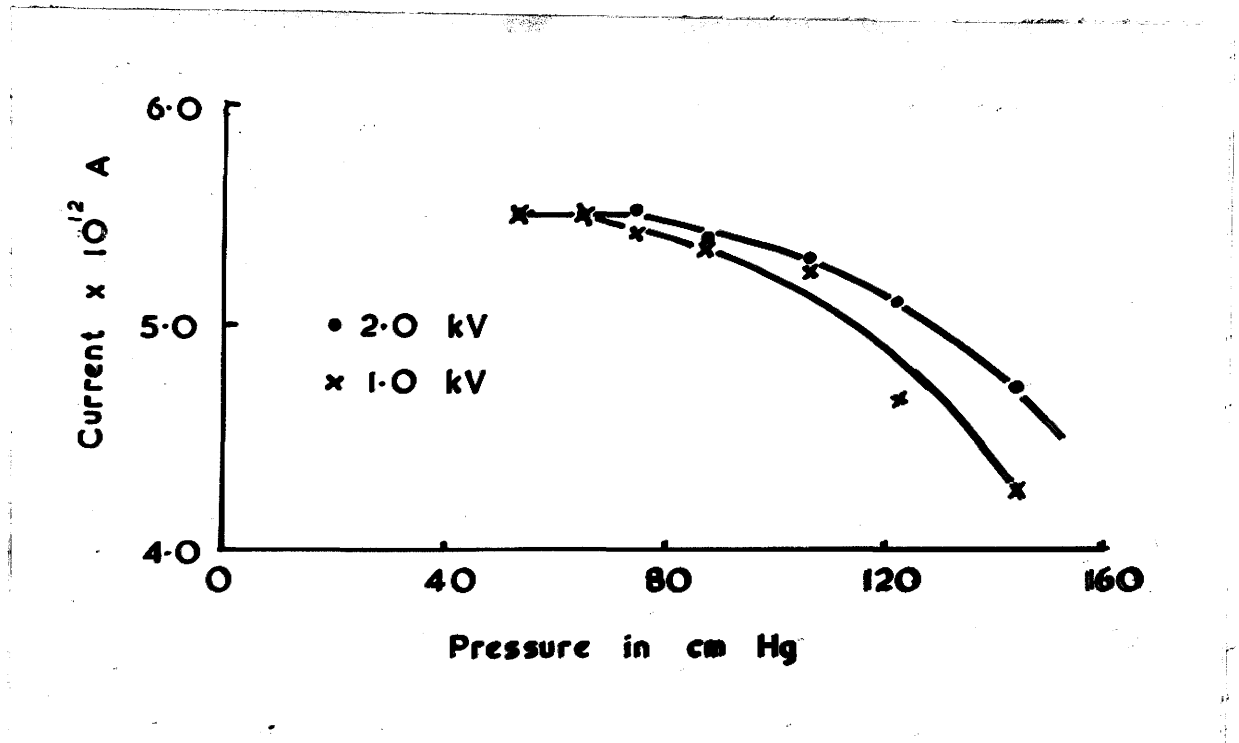
Fig. 30.

Variation of ionization current with pressure in air.

obtaining saturation ion currents.   The two values of the
ratio Vair/V_A obtained were 1·37 and 1·35 giving a mean of 1·36.

  (iii) <u>Oxygen.</u>

    Difficulty was again experienced in obtaining saturation
ion currents and so the above procedure was repeated.   The final
ratio of V_{O_2}/V_A = 1·24 was obtained.

  (iv) <u>Helium.</u>

    A total pressure of 4 atm. helium was required to stop all
the α -particles in the gas.   Even with this pressure saturation
currents were obtained with low applied voltages as can be seen
from fig. 31 curve (a).   When $\sim$ 2 atm. A were added to give
$\sim$ 30% A mixture complete saturation was not achieved below
2000V (fig. 31 curve (b)).   Saturation was, however, obtained for
a 15% A mixture.   A He – A mixture curve was plotted, the only
doubtful point being at 30% A as this had to be obtained by
extrapolation.   The general shape of the curve would not be
altered by a small change in the position of this point.

  (v) <u>Hydrogen.</u>

    The total pressure of hydrogen required was 3 atm.
Addition of 1½ atm. A gave a 30% A mixture and in both cases
saturation ion currents were obtained for applied voltages of less
than 2000V.   The ratios V_{H_2}/V_A = 1·43 and 1·38 gave a mean of
1·40.

  (vi) <u>Methane.</u>

    1/
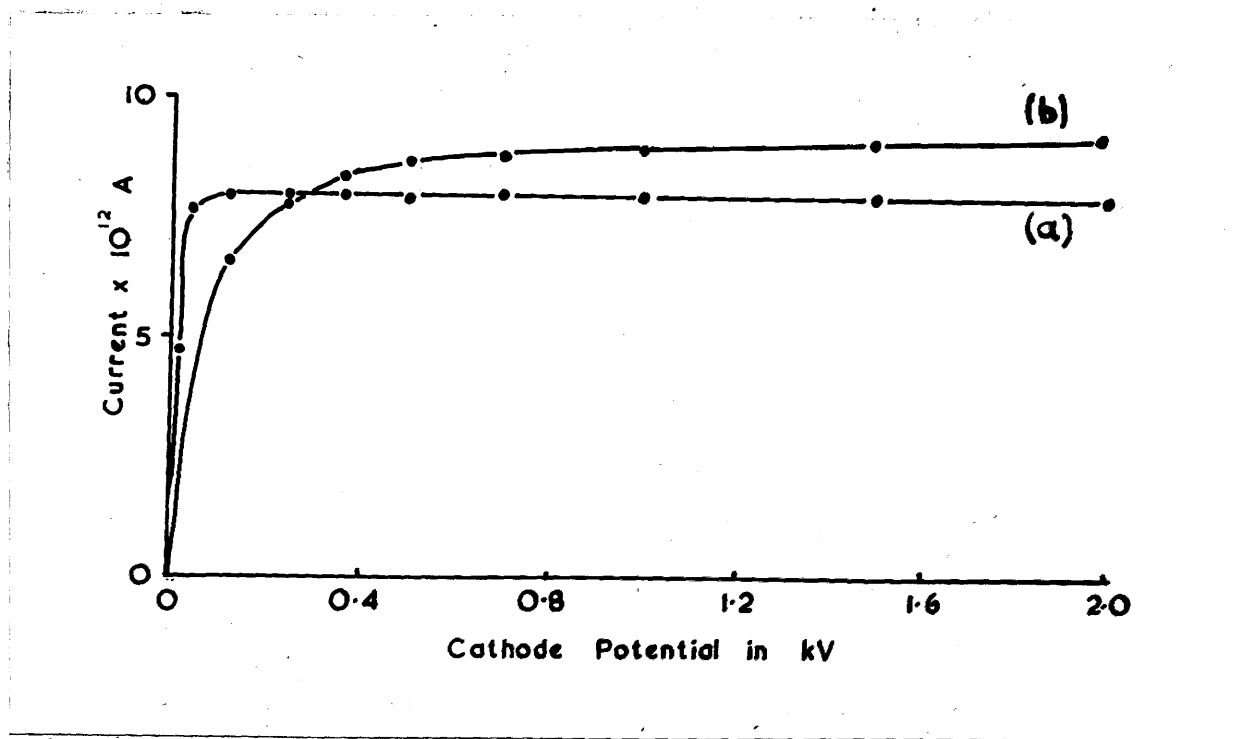
Fig. 31.

Current – voltage characteristic of Po ∝ –particles in
helium and helium + argon mixture.

1 atm. of methane was sufficient to stop all the α -
particles and no difficulty was encountered in achieving
saturation ion currents.   The final ratio $V_{CH_4}/V_A = 1 \cdot 10$ was
obtained.

The mixture curves are shown in fig. 32 and the numerical
values are summarized in table VIII, together with the previously
determined values for electrons and the results of Bakker and
Segré (1951) for 340 MeV. protons.   As in the electron case
allowance has been made for the $6 \cdot 5\%$ N_2 impurity in the methane.

Fig./

Fig. 32.

Ratio of ion currents in gas mixtures. (Po α-particles).

Argon with (a) methane, (b) helium, (c) hydrogen, (d) nitrogen.

Table VIII

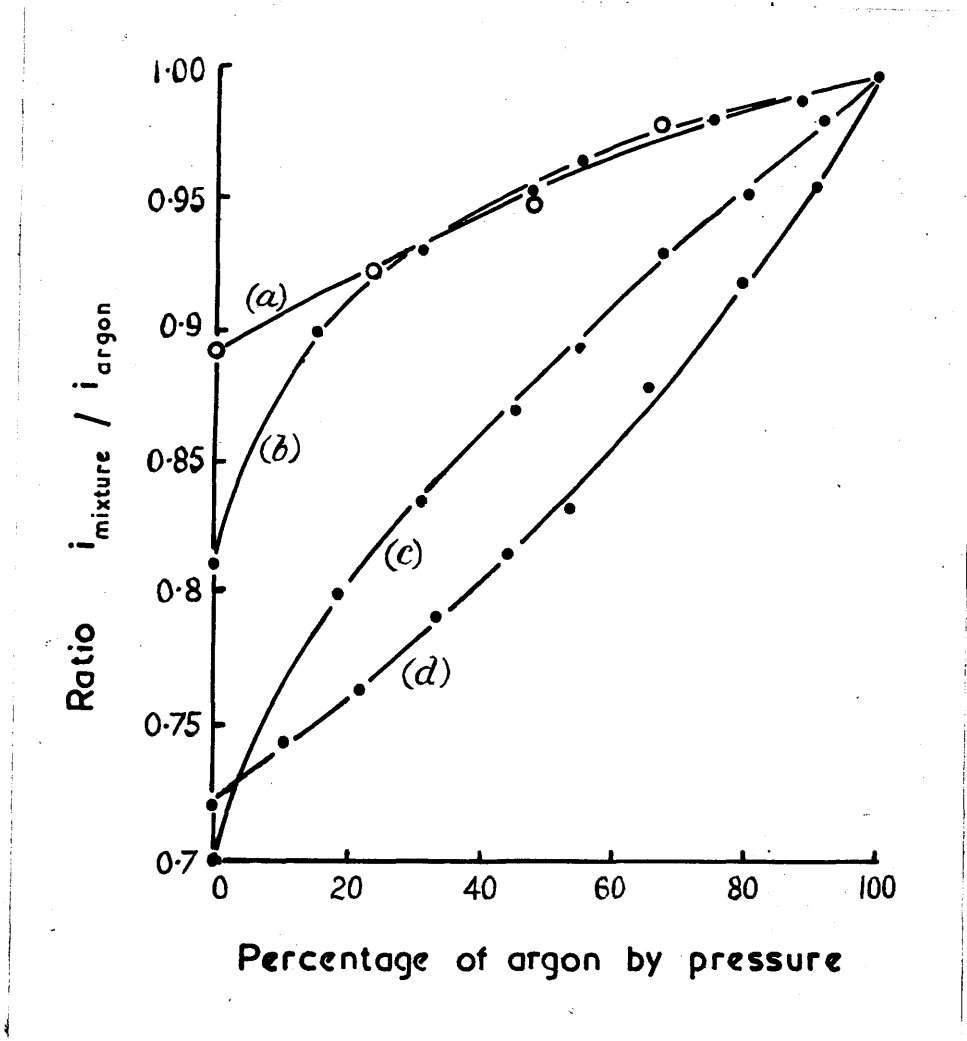| Gas | Electrons | | Po α-particles | | 340 MeV protons |
	V in ev	Vgas/V_A	V in ev	Vgas/V_A	Vgas/V_A
A	27·0	1·00	25·9	1·00	1·00
He	32·5	1·20	31·7	1·22	1·17
H_2	38·0	1·41	37·0	1·43	1·38
N_2	35·8	1·32	36·0	1·39	1·31
Air	35·0	1·29	35·2	1·36	1·30
O_2	32·2	1·19	32·2	1·24	1·23
CH_4	29·5	1·09	28·4	1·10	-----

6. Discussion of Results.

(i) Numerical Values.

The absolute value of V_A = 25·9 eV., obtained with Po α-particles is in fairly good agreement with the value of 25·4 eV. extensively used, but it is low compared with the more recent value of 28·3 eV. obtained by Cranshaw & Harvey (1948). It should be noted, however, that their results on the variation of V_A with α-particle energy are in marked contrast to those of Jesse, Forstat and Sadauskis (1950). A possible source of discrepancy is discussed by Hanna (1950). Jesse et al. measured the total ionization/

ionization using a slow recorder while Cranshaw & Harvey measured only the total available ionization.   The latter method might miss delayed secondary electrons from metastable argon atoms and so tend to give higher values for V.   As the present work employed a total ionization method, the lower value would be expected.   Indirect evidence in support of the value of V_A = 25·9 eV. is obtained by consideration of the values V_{N_2} = 36·0 eV. and Vair = 35·2 eV. derived using this value of V_A together with the measured ratios.   These derived values are in good agreement with the recent values of V_{N_2} = 36·3 $\overset{+}{-}$ 0·4 eV., Vair = 34·7 $\overset{+}{-}$ 0·5 eV. obtained by Alder, Huber & Metzger (1947) and the value of Vair = 35·1 eV., for Ra C$'$ α -particles quoted by Gray (1944). The ratios Vgas/V_A are unlikely to be much in error and a value of V_A = 28·3 eV. would give V_{N_2} = 39·5 eV. — a value higher than any obtained by recent workers.

Schmieder (1939) used Po α -particles to measure V for various gases.   Air was used as a standard gas and the following absolute values derived :–

Vair = 34·8, V_{N_2} = 36·1, V_{O_2} = 32·4, V_{CH_4} = 29·4, V_A = 24·4 . Except for the argon value which is lower than the 25·9 eV. obtained in the present work these values are in fair agreement with those in table VIII.   Dick et al. (1947) also found V for nitrogen, oxygen, and methane relative to Vair;   their absolute values/

values are, however, much lower than those obtained by the author.   This is due to the fact that the value they obtained for Vair was 32·1 eV.

There is little information available for comparison in the case of the light gases.   Gray (1944) derived the value of V_{H_2} = 36·0 eV. from the measurements of Taylor (1911, 1913). The relative measurements by Gurney (1925) are discussed by Rutherford, Chadwick & Ellis (1930) and the values of V_{H_2} = 33·0 , V_{He} = 27·8 eV. are quoted; Vair = 35 eV. was used as a standard. Using specially purified gas Naidu (1934) measured the relative total ionization produced by Po α -particles in helium and air and obtained an ionization ratio of 1·146.   For comparison this ratio in the present work is 1·11.

From table VIII it can be seen that the relative values obtained with α -particles are very close to those obtained with electrons except in the case of nitrogen and air.   This may be due to an increase in V_{N_2} for low energy electrons.   From a consideration of the results given in chapter V this increase is unlikely to take place for electrons of energy $>$ 200 eV.

(ii) **Mixture curves.**

The ionization of mixtures of gases by α -particles has been discussed by Huber, Baldinger & Haeberli (1950) who derived an expression for the variation of Vmixture with the partial pressures and stopping powers of the component gases.

For/

For a mixture the energy loss per ion pair is defined as $V_m = \Delta E/\Delta n.$ ΔE is the energy loss of the α-particles and it is equal to the sum of the energy losses for the production of the primary ions in the two gases, i.e. $\Delta E = \Delta E_1 + \Delta E_2.$ The number of ions Δn is the sum of those produced directly by the α-particles and indirectly by the secondary δ-rays and light quanta.

Let the average energy expenditure per ion pair in the pure gases be V_1 and V_2 respectively and also assume that the numbers Δn_1 and Δn_2 of the ions of the two gas components are completely determined from the equations,

$$\Delta n_1 = \frac{\Delta E_1}{V_1} \quad , \quad \Delta n_2 = \frac{\Delta E_2}{V_2}$$

This assumption means that the gases behave independently of one another. In particular, the ionizing effect of the δ-electrons and of the light quanta of one gas with respect to the other is completely neglected. (In practice the ions created in one gas by δ-electrons and light quanta from the other gas will to a certain extent be compensated for by the ions created in the converse process, so that this assumption is not so improbable as it first appears.)

Hence $\Delta n = \Delta n_1 + \Delta n_2 = \dfrac{\Delta E_1}{V_1} + \dfrac{\Delta E_2}{V_2}$

$\therefore \dfrac{1}{V_m} = \dfrac{\Delta E_1}{\Delta E_1 + \Delta E_2} \cdot \dfrac{1}{V_1} + \dfrac{\Delta E_2}{\Delta E_1 + \Delta E_2} \cdot \dfrac{1}{V_2}$

$E_1/$

ΛE_1 and ΛE_2 are proportional to the product of the atomic stopping power, s, and the partial pressure p of the gas components.

$$\therefore \quad \frac{1}{V_m} = \frac{s_1 p_1}{s_1 p_1 + s_2 p_2} \times \frac{1}{V_1} + \frac{s_2 p_2}{s_1 p_1 + s_2 p_2} \times \frac{1}{V_2}$$

$$\text{or} \quad \frac{1}{V_m} = \frac{s_1 p_1}{s_1 p_1 + s_2 p_2} \times \left(\frac{1}{V_1} - \frac{1}{V_2} \right) + \frac{1}{V_2}$$

Thus to a first approximation $\frac{1}{V_m}$ is linearly dependent on

$$z = \frac{s_1 p_1}{s_1 p_1 + s_2 p_2} \quad .$$

For the purposes of comparison with experiment the following values of stopping power, relative to air as unity, are used. $S_A = 0 \cdot 929$, $S_{H_2} = 0 \cdot 224$, $S_{N_2} = 0 \cdot 99$, $S_{He} = 0 \cdot 18$. The first three values are due to Gray (1944) and take into account the results obtained by several different experimenters. The figure for helium is obtained from Haeberli, Huber & Baldinger (1950). In figs. 33, 34 and 35 $1/V_m$ is plotted as a function of z for ionization by α-particles in A - H_2 , A - N_2 and A - He mixtures. These curves are also available for slow electrons from [37] A. Since the energy of these electrons ($\sim 2 \cdot 7$ keV.) is of the same order of magnitude as the energy of the secondary δ-rays produced by the α-particles, the electron curves may be considered as secondary/
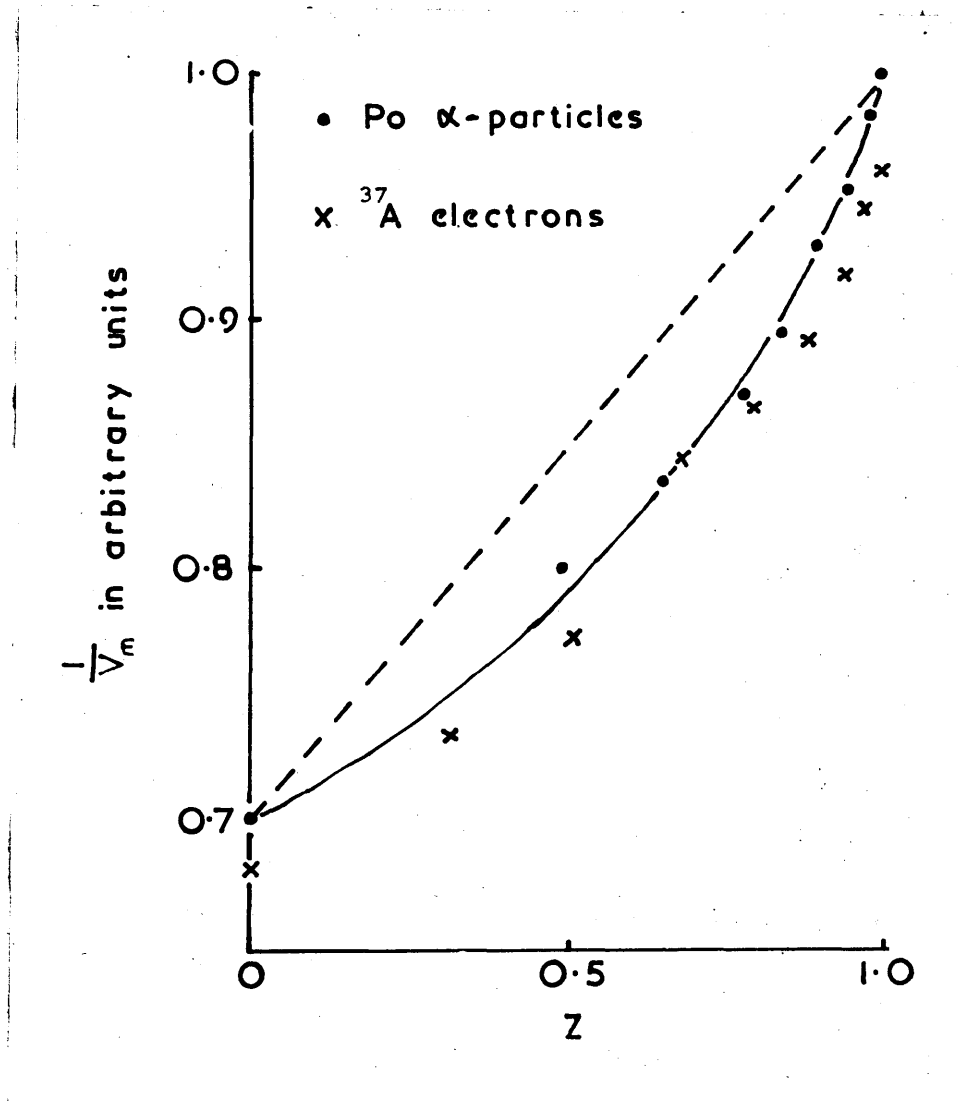
Fig. 33.
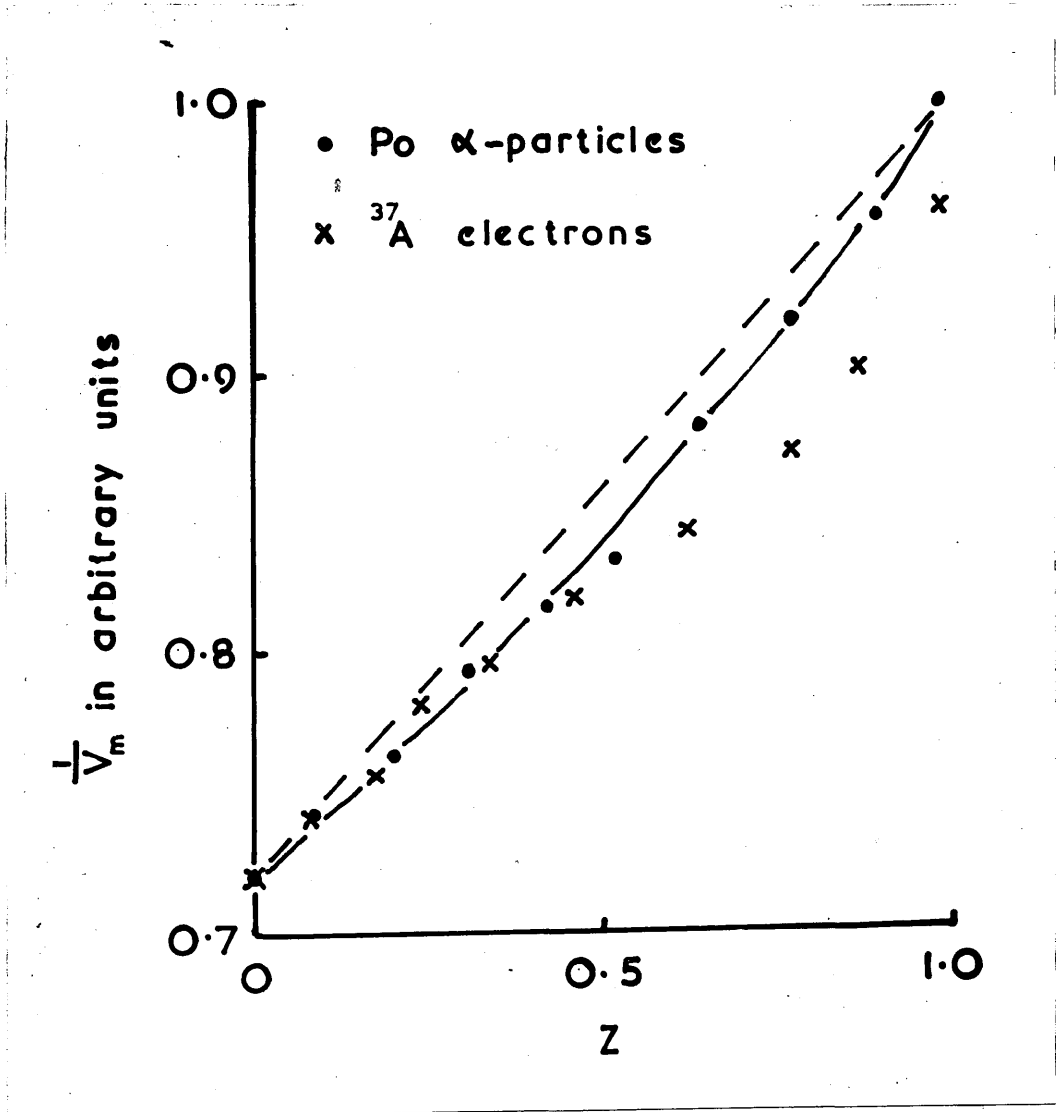
Variation of $1/V_m$ with Z for argon-hydrogen mixtures.

Fig. 34.

Variation of $1/V_m$ with Z for argon-nitrogen mixtures.
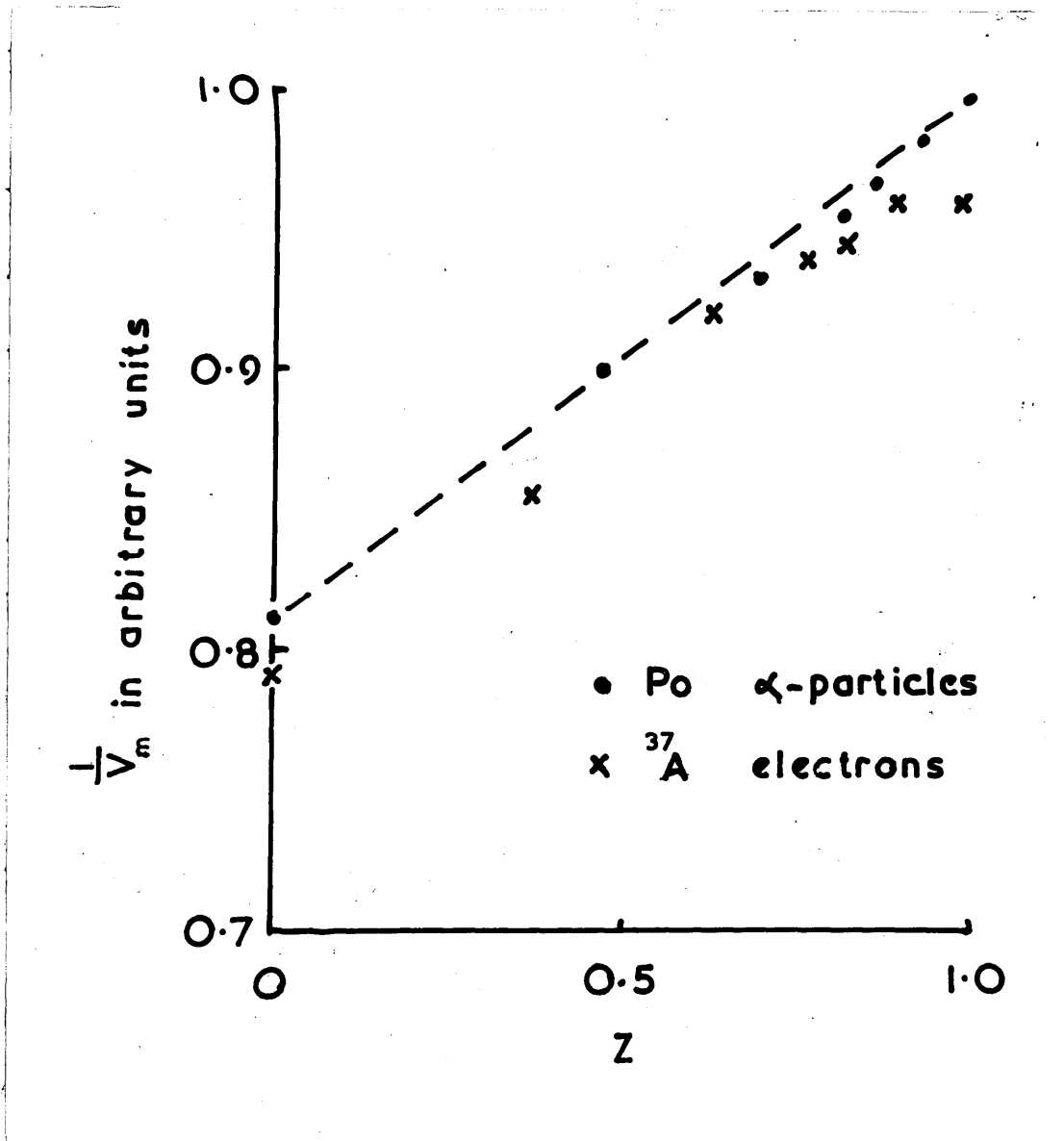
Fig. 35.

Variation of $1/V_m$ with Z for argon-helium mixtures.

secondary ionization curves and the α curves as total (primary + secondary) ionization curves.   Thus for the purpose of comparison the electron curves are also shown in figs. 33, 34 and 35.   (The same α -particle values of stopping powers were used in the calculation of z).   In addition the difference in the absolute values of V for electrons and α -particles has been taken into account so that the curves give a true representation of the variation of $\frac{1}{V_m}$ with z in the two cases.   In each graph the straight line expected in the α -particle case, on the grounds of the above theory, is shown dashed.

A considerable deviation from the straight line is shown in fig. 33 for an A - H_2 mixture.   There is also a small difference in the absolute values for electrons and α -particles, which cannot be explained on this picture, but in general the points for α -particles and electrons lie near the same curve. The second mixture, that of A - N_2 is shown in fig. 34.   The α -particle case gives a smooth curve differing by a maximum $\sim 3\%$ from the straight line.   From 100% N_2 to a 50 - 50 A - N_2 mixture the electron values are very close to the corresponding α values.   With increasing pressure of argon up to 100% A, however, the electron points are seen to lie considerably below the α curve.   In fig. 35 the curves for an A - He mixture are shown./

shown.   There is a difference in the absolute values of V

obtained for both argon and helium, but in the middle of the

curve the α and electron points lie close together and do not

differ significantly from a straight line.

It is possible to derive a different expression for V_m

without making the drastic assumption that the gases behave

independently of one another.   Instead of considering the total

number of ions, Δn, as the sum of the numbers of the ions of

the two gas components, it can be determined as a sum of the

numbers of ions produced in primary ionizations and by secondary

δ -rays.

$$\text{i.e.} \quad \Delta n \;=\; \Delta n_1 + \Delta n_2 + \Delta n_s \;.$$

Δn_1 and Δn_2 are the numbers of primary ions produced in

the two components and

$$\Delta n_1 \;=\; \frac{\Delta E_1}{V_{p_1}} \quad , \quad \Delta n_2 \;=\; \frac{\Delta E_2}{V_{p_2}}$$

where ΔE_1 and ΔE_2

are the energy losses for the production of primary ions and

V_{p_1} and V_{p_2} are the average energy expenditures per primary

ion pair.   If ΔE is the energy loss of the α -particles in

the mixture then, as before,

$$\Delta E_1 \; / $$

$$\Delta E_1 = \Delta E \frac{s_1 p_1}{s_1 p_1 + s_2 p_2} = \Delta E \, z$$

and $$\Delta E_2 = \Delta E \frac{s_2 p_2}{s_1 p_1 + s_2 p_2} = \Delta E \, (1 - z)$$

If $\overline{I_1}$ and $\overline{I_2}$ are mean ionization potentials of the two gases then the kinetic energy of the secondary δ-rays produced is $(T_1 + T_2)$ where,

$$T_1 = \Delta E_1 - \Delta n_1 \overline{I_1} = \Delta E \, z - \Delta n_1 \overline{I_1}$$

and $$T_2 = \Delta E_2 - \Delta n_2 \overline{I_2} = \Delta E \, (1 - z) - \Delta n_2 \overline{I_2} .$$

This if V_e is the average energy expenditure per ion pair for δ-rays in the gas mixture then the number of ions produced by the δ-rays is $\Delta n_s = \dfrac{T_1 + T_2}{V_e}$

$$\therefore \Delta n = \frac{\Delta E_1}{V_{p_1}} + \frac{\Delta E_2}{V_{p_2}} + \frac{T_1 + T_2}{V_e}$$

Hence

$$\Delta n = \Delta E \left(\frac{z}{V_{p_1}} + \frac{1 - z}{V_{p_2}} \right) + \frac{\Delta E z + \Delta E (1 - z) - \Delta n_1 \overline{I_1} - \Delta n_2 \overline{I_2}}{V_e}$$

$$= \Delta E \left[z \left(\frac{1}{V_{p_1}} + \frac{1}{V_e} \right) + (1 - z) \left(\frac{1}{V_{p_2}} + \frac{1}{V_e} \right) \right] - \frac{\Delta n_1 \overline{I_1}}{V_e} - \frac{\Delta n_2 \overline{I_2}}{V_e}$$

But/

But $\Delta n_1 = \dfrac{\Delta Ez}{V_{p1}}$ and $\Delta n_2 = \dfrac{\Delta E\,(1-z)}{V_{p2}}$

$\therefore \dfrac{\Delta n}{\Delta E} = \dfrac{1}{V_m} = z\left(\dfrac{1}{V_{p1}} + \dfrac{1}{V_e} - \dfrac{\overline{I_1}}{V_e V_{p1}}\right) + (1-z)\left(\dfrac{1}{V_{p2}} + \dfrac{1}{V_e} - \dfrac{\overline{I_2}}{V_e V_{p1}}\right)$

This expression is still formally linear in z but a graph of $1/V_m$ against z will be a straight line only if V_{p1} , V_{p2} and V_e are constants with respect to z. V_{p1} and V_{p2} are independent of z but V_e varies with z as seen from the electron curves in figs. 33, 34 and 35. The equation for $1/V_m$ may be re-written in the form,

$$\frac{1}{V_m} = \frac{1}{V_e} + \frac{1}{V_{p2}}\left(1 - \frac{\overline{I_2}}{V_e}\right) + z\left[\frac{1}{V_{p1}} - \frac{1}{V_{p2}} - \frac{1}{V_e}\left(\frac{\overline{I_1}}{V_{p1}} - \frac{\overline{I_2}}{V_{p2}}\right)\right] \qquad (3)$$

In this expression $1/V_e$ is the dominant term and so, as a first approximation, $V_m = V_e$ for a given z. Thus, if $1/V_m$ is plotted against z, the α -particle and electron curves will be nearly coincident. The remaining terms give the amount of separation of the curves. Were these terms constant the two curves would be parallel; since they contain V_e, which is dependent on z, the separation of the curves will vary with z. Furthermore, the correction term is always positive and so the α -particle curve would be expected to lie above the electron curve in every case. That these conclusions are justified in practice can be seen from figs./

118.

figs. 33, 34 and 35.

For a pure gas $z = 0$ or 1 and equation (3) reduces to

$$\frac{1}{V_m} = \frac{1}{V_e} + \frac{1}{V_{p_1}}\left(1 - \frac{\overline{I_1}}{V_e}\right) \text{ or } \frac{1}{V_e} + \frac{1}{V_{p_2}}\left(1 - \frac{\overline{I_2}}{V_e}\right)$$

For pure argon, V_m is the value of V_A for α-particles $\simeq$ 26eV. and $V_e = 27$eV. If the lowest ionization potential = 15·3 eV. (Rutherford, Chadwick & Ellis, 1930, p.81) is taken for $\overline{I_1}$ then V_{p_1} can be calculated. The value obtained $V_{p_1} \sim 280$ eV. is much higher than expected. (The theoretical values of V_p for nitrogen and hydrogen are $\sim$ 80 and 100 eV. respectively, Mott & Massey, 1949, p.255). This discrepancy can be interpreted as meaning that $\overline{I_1}$ is greater than the lowest ionization potential. The difference arises from three causes (a) An α-particle will excite certain atoms in passing, without ionizing them. (b) It may excite the residual ion as well as producing a δ-ray. (c) The δ-ray may be produced from an inner level. A value of $\overline{I}$ = 23 eV. would give a value for $V_{p_1} \sim 100$ eV. This value for $\overline{I_A}$ is similar to the value of 25eV. deduced by Townsend (1947) p. 110 for an average ionization potential for slow electrons in air.

It would have been possible to derive more information of this type by using the values of V obtained for the various gases and/

and fitting them into the above equations. The basic assumption, that the ^{37}A electrons are equivalent to δ-rays, is only true to a first approximation, however, and only a qualitative explanation of the experimental results appears to be justified. More reliable quantitative information might be derived from a study of very slow δ-rays in gas mixtures.

Chapter VII

Theory

The application of wave mechanics to the penetration of atomic particles through matter has recently been the subject of a comprehensive review by Bohr, (1948). In particular the stopping power and ionization effects of particles in light substances are discussed and an expression is derived for the total number of collisions leading to ionization in the case of a primary particle. For comparison with the results of experiments described in the previous chapters an expression for the total (primary + secondary) ionization is required. As pointed out by Bohr ,..."an accurate estimate of the secondary ionization presents a very complicated phenomenon which can be treated only approximately on present theories ...". Before discussing the attempts by various authors to give an approximate solution of the problem it is profitable to summarize the general trends of the experimental results for the determination of the average energy expenditure per ion pair.

An adequate theory should be able to account for the following general conclusions drawn from a review of the experimental results.

(a) V is largely independent of the energy of the primary particle down to very low energies. Further, the values of V obtained for a particular gas are similar for ionization by electrons/

electrons, protons and α -particles.   Heavy ions such as ^{7}Li
and fission fragments have also been found to give similar values
for V.

(b)   Although V varies from gas to gas the values, for the
common gases at least, are contained in the relatively small range
of 25 - 40 eV.   There is no general correlation between V and the
lowest ionization potential of the gas;   in particular V is low for
the noble gases, such as argon and helium, whereas their ionization
potentials are unusually high.

A general explanation of (a) has been given by Williams
(1932), following a result due to Bethe (1930).   V must always be
greater than the ionization potential I because part of the
energy absorbed by a substance goes into processes other than
ionization and may be considered as "wasted" energy.   Most of this
"wasted" energy goes into the excitation of optical levels and
ultimately into the production of light.   The collisions made by
a heavy particle traversing matter may be roughly divided into
three groups. (i) excitation collisions in which ionization does
not take place (ii) light ionization collisions in which the
energy lost is of the order of the ionization potential I,   (iii)
violent collisions in which high speed secondary electrons are
produced.   According to Williams, Bethe has shown theoretically
that the relative numbers of excitation collisions and light
ionization/

ionization collisions are practically independent of the nature and velocity of the primary particle. This means that a constant amount of "wasted" energy is associated with the formation of an ion pair and so, neglecting violent collisions, V should be approximately constant. The relative numbers of high speed secondary electrons produced in violent collisions is, of course, dependent on the energy of the primary particle, but violent collisions are infrequent and contribute little to the final total ionization. The high speed secondary electrons also dissipate most of their energy ultimately in the form of light collisions and since, as has been stated, for such collisions the "wasted" energy per ionizing collision is a constant, it does not matter whether the ionizing particle is the primary particle or a fast secondary electron. Hence for a given energy loss by the primary particle the total ionization is nearly independent of its nature and velocity.

An explanation of (b), particularly the lack of correlation between V and I, is a much more difficult problem. Bethe (1930) made a "hydrogen-like" approximation in which each molecular electron is treated as though it belonged to a hydrogen-like atom. Bagge (1937) based his calculations on the Thomas-Fermi model of the atom apart from replacing the theoretical ionization potential of each molecule by the corresponding/

corresponding experimental value. Since both these theories lead to a positive correlation between V and I , contrary to the experimental results, they will not be discussed in detail. Williams (1932) used Bethe's formula and satisfied his first condition ($u^2/v^2 \approx I/\frac{1}{2}mv^2 \lll 1$, where v is the velocity of the moving particle and u is the Bohr orbit velocity) by neglecting secondary electrons with energies of less than 10 I. He could not definitely evaluate the contribution of such electrons but fixed limits corresponding to zero and 100% efficiency. In this way the values V ~ 35 to 50 eV. for hydrogen and V ~ 55 to 80 eV. for helium, were obtained. The observed values for hydrogen are just within the limits given but for helium even the theoretical lower limit is nearly twice the observed value.

The most promising approach to the problem is due to Fano (1946) who explained qualitatively the lack of correlation between V and I and gave an approximate calculation for the numerical evaluation of V in the cases of atomic hydrogen and helium. Fano considered the method of absorption of the energy of an ionizing radiation by a molecule to be by the dipole oscillation of its electronic charge. On this picture the lower frequency oscillations lead to excitation while those of higher frequency lead to ionization of the molecules. Fano defined the oscillator strength/

strength of a process as "the proportion of oscillators whose
frequency corresponds to any particular process of energy
absorption by the gas molecules".   The amount of energy "wasted"
in excitation without ionization can then be found from the sum
of the oscillator strengths of all the excitation processes
available to the molecule.   Table IX, given by Fano, shows the
available theoretical information on oscillator strengths of
excitations and shows that for three characteristic atoms the
"wasted" energy might be expected to be an inverse function of I.

<p style="text-align:center"><u>Table IX</u></p>

Substance	H	He	Li
I in eV.	13·5	24·5	5·4
Oscillator strengths of all excitations	57%	21%	88%

In particular, the low value of V for helium is understandable on
this picture.   In view of this success, Fano set out to formulate
a theory which would explain the relatively small percentage of
excitations (giving a small energy waste) in substances like
helium.   This will now be discussed in greater detail.

Bethe (1930) had assumed that a hydrogen atom and a
hydrogen/

hydrogen-like atom could be treated as dynamically similar systems and this led to a proportionality between V and I.   By comparing the ground state and excited states of hydrogen and helium, Fano discovered a marked departure from dynamic similarity between the two atoms.   In particular Bethe had only accounted for the screening of an outer electron by the inner electrons by replacing the actual atomic number Z by a lower effective number Z - s.   (s is called the inner screening number). In addition to this inner screening Fano inserted a term, S, to account for the outer screening effect due to that part of the electronic cloud further away from the nucleus than the electron under consideration.   By using this outer screening term, Fano succeeded in taking into account the lack of similarity between different atoms;   failure to do this had been the great weakness of Bethe's theory.   S is zero in the case of atomic hydrogen, negligible in the case of alkali atoms, but important in the case of helium and atoms in which there are many electrons in the outermost shell.   The binding energy of an electron of total quantum number n changes from $(Z - s)^2 \, Ry/n^2$ on Bethe's theory to $(Z - s)^2 \, Ry/n^2 - eS$ on Fano's theory.   Thus energy absorptions which would only be sufficient to excite a hydrogen-like atom with atomic number (Z - s) may result in ionizations because of the/

the reduced binding energy due to outer screening. This means that in substances with a large S value (for example, helium) there will be fewer excitations and so less energy waste. Table IX is seen to be in agreement with this general picture. Born (1935) pp. 163-5 has given a complete table in which the number of electrons in the various shells and also the lowest ionization potential are listed for each element. This shows that the number of electrons in the outermost shell, and hence S, increase as I increases. In fact the variation in ionization potential and energy waste appear to be correlated in such a way as to minimize the variations of V.

In order to make even an approximate calculation for V it must be assumed that particles of different charge, mass and velocity are equally efficient ionizing agents. This has already been justified theoretically and has been found to be very nearly true in practice. The three types of collision previously discussed will be considered to contribute to the total cross section i.e. $\sigma = \sigma_e + \sigma_{i_1} + \sigma_{i_2}$ where σ_e refers to excitation collisions, σ_{i_1}, to light ionization collisions where the ejected electron has energy $< I$ and σ_{i_2} to violent collisions where the ejected electron has energy $> I$. The corresponding energy losses are E_e, E_{i_1} and E_{i_2}. E_{i_2} consists of energy I lost in ionization + $(E_{i_2} - I)$ which is the energy of/

of the secondary electron produced. This secondary electron is identical in ionizing properties to the original particle, according to the basic assumption, so we may consider the primary particle to have lost only energy I and there to have been no secondary electron produced. Hence,

* (see below)

$$V = \frac{(\sigma_e E_e + \sigma_{i_1} E_{i_1} + \sigma_{i_2} I)}{(\sigma_{i_1} + \sigma_{i_2})} \tag{4}$$

This equation can be evaluated directly in the case of atomic hydrogen only, in which case V was found by Fano to be ~ 36 eV. For comparison with experiment only molecular hydrogen values are available and the results V = 38·0 eV. for electrons and V = 37·0 eV. for α -particles obtained by the author are in fair agreement with the calculated value.

In order to apply eqn. (4) to other substances Fano makes two simplifying assumptions. Light and violent ionizing collisions are identified with grazing and head-on impacts and all collisions are considered to be one or other of these extreme types As a first approximation Fano makes the drastic simplification of assuming that only grazing collisions occur, i.e. σ_{i_2} is assumed to be zero. This reduces eqn. (4) to,

$$V_1 = (\sigma_e E_e + \sigma_{i_1} E_{i_1}) / \sigma_{i_1}$$

The probability of photoexcitation per unit time, from an initial state o to a final state f, is given by Heitler (1944) p.90 eqn.

42/

42 as,

$$w_{o-f} = \frac{2\tilde{\pi}}{\hbar} \left| H'_{o-f} \right|^2 \rho_f$$

where H'_{o-f} = matrix element for absorption of light quantum + transition o - f and ρ_f = density of final states. The cross-section for a transition is the probability of excitation if one incoming particle is crossing unit area in unit time. If we consider a volume of area A and thickness d then in unit time there will be $\frac{c}{d}$ photons crossing area A. Thus $\frac{c}{Ad}$ photons will cross unit area in unit time. If Ad = V, the volume of normalization, the cross-section can be written,

$$\sigma_{o-f} = \frac{2\tilde{\pi}}{\hbar} \frac{V}{c} \left| H'_{o-f} \right|^2 \rho_f$$

In the present case we are dealing with the dipole approximation and the probability of transition of an atom from the ground (0th) to the jth excited or ionized state is then proportional to the square of the dipole matrix element, $x_o = \int \psi_j x \psi_o d\tilde{\tau}$
The total cross-sections for excitation or ionization can then be written in the form,

$$\sigma_e = \text{const.} \sum_{ej} x_{jo}^2 \qquad \text{summing over excited states}$$
$$\sigma_i = \text{const.} \sum_{ij} x_{jo}^2 \qquad \text{summing over ionized states.}$$

The latter is actually an integration and its value is denoted by x_i^2. Using the above equations together with the Thomas-Kuhn sum/

sum rule Fano evaluated the sum, $\sigma_e E_e + \sigma_i E_i$ = const. x Ry where Ry is the Rydberg energy.   Hence for the first approximation

$$V = Ry/x_i^2$$

For atomic hydrogen $x_i^2 = 0\cdot283$ and hence V = 48 eV.   This is greater than the previously calculated value and also the experimental value but as only one type of ionizing collision has been considered the waste of energy due to excitations would be expected to be more important and lead to a value of V which was too high.

Fano has also calculated x_i^2 in the case of helium, using hydrogen-like wave functions with Z = 27/16 for the ground state and Z = 1 for excited and ionized states.   The value obtained is V = 53 eV. which is much closer to the hydrogen value than the result of V = 87 eV. obtained by using the average value Z = 1·35 for all the states.   Use of a single value of Z is shown to lead to the conclusion that $x_i^2 \propto 1/Z^2$.   This would give $V \propto I$ which is the failure of the earlier theories.

As a second approximation the other extreme type of collision, head on inelastic impacts, is also taken into account. Using Born's approximation to the theory of inelastic impacts Fano succeeds in showing that the effect of outer screening is of sufficient/

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sufficient importance to cancel the difference in the
ionization potentials of hydrogen and helium. The numerical
values obtained are $V_H = 36$ eV. , $V_{H_e} = 38$ eV. This latter
value is still considerably greater than the measured one of
~ 32 eV. but further corrections which cannot be easily
evaluated numerically would tend to reduce the value obtained for
V.

* As pointed out by G. Erskine (1953, Ph.D. Thesis, London)
there is an error in Fano's paper. This arises
because ejected electrons with kinetic energy
less than I will do no more ionizing. ie.
energy $2I$ is lost. Eqn. 4 should read,

$$V = \frac{\sigma_e E_e + \sigma_{i_1} E_{i_1} + \sigma_{i_2}(2I)}{\sigma_{i_1} + \sigma_{i_2}}$$

This leads to a value of $V \sim 45 eV$ for helium.
This is in good agreement with recent experimental
values for α-particles in very pure helium.

Chapter VIII

Recent Work on the Energy Expenditure per Ion Pair.

Since the experiments described in the previous chapters were completed more information has become available. Hardwick (unpublished) has recently investigated the ionization of various gases by electrons by determining the ion pair yields for tritium using a calorimetric method of measurement. The preliminary values obtained for V for the relevant gases are shown in table X.

Table X

Gas	V in eV.	V_{gas}/V_A
A	28·78	1·00
He	33·33	1·16
H_2	40·65	1·41
N_2	38·30	1·33
Air	36·73	1·28
O_2	34·01	1·18
CH_4	30·24	1·05

The ratios V_{gas}/V_A are close to those obtained by the author (table VIII p.106) but the absolute values are, on the whole, ~ 6% higher than those in table VIII. In a private communication, however, Dr. Hardwick emphasized the fact that his values were not final and he thought that a re-determination of one of his standards/

standards might reduce his values by ∼ 5%. Taking this into account the agreement between the two sets of results is fairly good although the methods used were quite independent. In chapter IV it was stated that the value of V_{N_2} = 35·8 eV. obtained by the author was in agreement with the result of Gaertner (1934/5) rather than the more generally accepted value of 32·5 eV. obtained by Eisl (1929) and Gerbes (1937). The work of Hardwick is additional evidence in support of the higher value of V for nitrogen.

Two recent publications give absolute values of V for ionization by α -particles. Haeberli, Huber & Baldinger (1952) obtained the values V_A = 26·25, V_{H_e} = 30·86, V_{N_2} = 36·3 and V_{O_2} = 32·17 eV. It is claimed that these results are not in error by as much as ½%. Sharpe (1952) studied the ionization of Pu α -particles and obtained the values V_A = 26·3, V_{N_2} = 36·4 , V_{air} = 35·6 , V_{O_2} = 32·9 and V_{CH_4} = 29·1 eV., with an accuracy of 1%. Both these sets of results are very close to those obtained by the author. Sharpe also found that the ionization current in argon was increased by about 1% by the admixture of 2 to 5% of carbon dioxide or oxygen. This effect was attributed to the fruitful destruction of excited states in argon by the contaminant. In the work described in chapter VI the argon

always/

always contained $\sim$ 1 to 2% methane so that the effect described by Sharpe was not observed.

Appendix I.

Integral Evaluated by Dr. E. A. Power

The problem encountered in the evaluation of N (p.60) may be stated as follows.   A uniform distribution of sources is contained within a cylinder of radius a and length l.   The flux of particles through a sphere of radius r about a unit source is given as $N'e^{-\mu r}$; N' being a measure of the source strength. Find the net flux of particles through the surface of the cylinder as a percentage of the total.

Consider a source at O; the flux of particles through a sphere of radius r about O due to O is $N'e^{-\mu r}\, d\rho$ where $d\rho$ is the volume occupied by the source.   The flux of particles through solid angle $d\Omega$ at distance r about O due to O is

$$\frac{N'd\rho}{4\pi}\, d\Omega\, e^{-\mu r}$$

Now consider the flux of particles through a generator of the surface of the cylinder distance A from O
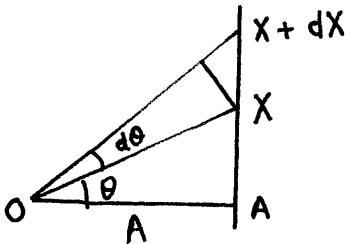
First consider flux through element dx of generator at a distance r from O. $\widehat{AOX} = \theta$. Let width of generator strip perpendicular to OAX be dy.

$\therefore$ Flux through dx $= \dfrac{N'd\rho}{4\pi}\, e^{-\mu r}\, \dfrac{r\,d\theta\,dy}{r^2}$ $\qquad$ since $d\Omega = \dfrac{r\,d\theta\,dy}{r^2}$

Now/

Now $\cos\theta = \dfrac{A}{r}$, thus flux through $dx\,dy$ due to 0

$$= \frac{N'd\rho}{4\pi} \cdot \frac{e^{-\mu r}}{r} \, d\theta \, dy = \frac{N'd\rho}{4\pi} \frac{e^{-\mu A/\cos\theta}}{A} \cos\theta \, d\theta \, dy$$

Thus total flux through generator due to source at 0

$$= \frac{N'd\rho}{4\pi} \frac{dy}{A} \int e^{-\mu A/\cos\theta} \cos\theta \, d\theta$$

Limits of θ :— when θ is large $e^{-\mu A/\cos\theta}$ becomes small and, as an approximation accurate everywhere except the ends of the cylinder, we assume an infinite generator and integrate over all θ . (The accuracy of this approximation will be discussed later).

Define $\quad F(A) = \dfrac{2}{A} \displaystyle\int_{0}^{\pi/2} e^{-\mu A/\cos\theta} \cos\theta \, d\theta$

Hence the total flux due to 0 through the generator considered is

$$\frac{N'd\rho\,dy}{4\pi} F(A)$$

Now, let us consider a plan view. Let C be the centre of the cylinder cut by a plane through 0 perpendicular to a generator.
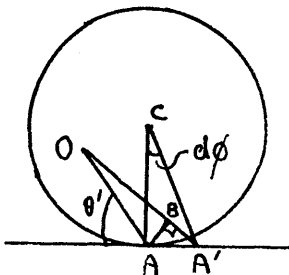
AC = 0. Consider the flux through element of surface made up of generator strip whose width is $AA' = a\,d\phi$ where AA' subtends angle $d\phi$ from C. Let OA make angle θ' with AA' as shown.
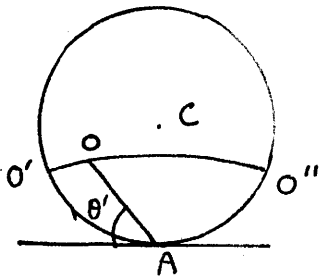
Now/

Now flux due to O through generator strip = $\dfrac{N'd\rho}{4\pi} F(A)$ AB

where AB = dy is perpendicular from A to OA'. $\sin.\theta' = \dfrac{AB}{AA'}$

$\therefore$ Flux due to O through generator strip considered

$= \dfrac{N'd\rho\, a}{4\pi} F(A) \sin\theta' d\phi$

The solution may be extended to include all sources on arc $O'O''$ radius A from A. Cylindrical co-ordinates with centre A may be used for element of volume $d\rho$.

$$d\rho = dz\, A\, dA\, d\theta'$$

where dz is the length of the element of source in direction of axis of cylinder.

$\therefore$ Flux due to all sources on arc $O'O''$ distance A to A + dA from A, and dz from plane $O'O''$ A is,

$$\dfrac{N'F(A)}{4\pi} dz\, A\, dA\, a\, d\phi \int \sin\theta' d\theta'$$

Limits for θ':— θ'_{min} to $\pi/2$ and $\pi/2$ to $\pi - \theta'_{min}$

where $\sin\theta'_{min} = A/2a$. Thus $\theta'_{min} = \sin^{-1} A/2a = \alpha$ say.

$\therefore$ Flux $= \dfrac{N'F(A)\, dz\, A\, dA\, a\, d\phi}{4\pi} \, 2\left[-\cos\theta'\right]_{\sin^{-1} A/2a}^{\pi/2}$

$= \dfrac{N'F(A)\, a\, A\, dz\, dA\, d\phi}{2\pi} \cos\left(\sin^{-1} A/2a\right)$

Thus total flux due to all elements of thickness dz from plane
$O'O''$ A/

$\overset{\cdot\cdot}{O}O''A$

$$= \frac{N'a\,dz\,d\phi}{2\tilde{\imath}} \int A\,F(A)\cos\alpha(A)\,dA$$

$\therefore$ Total flux Ψ due to all elements throughout the cylinder,

$$\Psi = N'aL \int_0^{2a} A\,F(A)\cos\alpha(A)\,dA$$

where L is the length of the cylinder.

Substituting for F(A) this expression becomes,

$$\Psi = 2N'aL \int_0^{2a} \int_0^{\tilde{\imath}/2} e^{-\mu A/\cos\theta} \cos\theta\cos\alpha\,d\theta\,dA$$

Since $\sin\alpha = A/2a$, $A = 2a\sin\alpha$ and $dA = 2a\cos\alpha\,d\alpha$

$$\therefore \Psi = 4N'a^2 L \int_0^{\tilde{\imath}/2} \int_0^{\tilde{\imath}/2} e^{-\lambda\sin\alpha/\cos\theta} \cos\theta\cos^2\alpha\,d\theta\,d\alpha$$

where $\lambda = 2a\mu$.

Consider integration over $d\alpha$ and let $\lambda/\cos\theta = \tilde{\tau}$ i.e. consider,

$$\int_0^{\tilde{\imath}/2} e^{-\tilde{\tau}\sin\alpha} \cos^2\alpha\,d\alpha$$

It can be shown that,

$$\int_0^{\tilde{\imath}/2} e^{-\tilde{\tau}\sin\alpha} \cos^2\alpha\,d\alpha = \tilde{\tau} \int_0^\infty \frac{J_1(x)}{x^2+\tilde{\tau}^2} \frac{dx}{x}$$

Hence

$$\Psi = 4N'a^2 L\lambda \int_0^\infty \frac{J_1(x)}{x} \left\{ \int_0^{\tilde{\imath}/2} \frac{d\theta}{x^2+(\lambda/\cos\theta)^2} \right\} dx$$

This means that we may integrate first over $d\theta$. When this integration has been performed the expression for Ψ becomes,

Thus/

$$\Psi = 2\tilde{\imath} N'a^2 L\lambda \int_0^\infty \frac{J_1(x)}{x^3} \left\{ 1 - \frac{\lambda}{(x^2+\lambda^2)^{1/2}} \right\} dx$$

Thus the fraction of the number of quanta which escape , $(1 - N)$,

$$= \frac{\Psi}{\text{total no. emitted in cylinder}} = \frac{2\pi N' a^2 L \lambda I}{N' \pi a^2 L} = 2\lambda I$$

where $\quad I = \int_0^\infty \frac{J_1(x)}{x^3}\left(1 - \frac{\lambda}{(x^2 + \lambda^2)^{1/2}}\right)dx$

I can be evaluated numerically for particular values of μ.   The ionization chamber used had a radius a $\sim$ 5 cm.   Since the absorption coefficients for 2·62 keV. quanta are similar for argon and nitrogen the value $\mu = 0\cdot 375$ cm.$^{-1}$ was used for both.   Hence $\lambda = 3\cdot 75$ and by numerical computation $I \doteqdot 0\cdot 201$.

$$\therefore \quad (1 - N) = 0\cdot 158 .$$

A correction must be applied to this estimate to account for the fact that the cylinder was not of infinite length.   A rough estimate may be obtained by considering the numbers of quanta which escape through the ends and through the surface of the cylinder to be proportional to their areas.

$\therefore$ $(1 - N)$ must be increased by an amount,

$$\sim \frac{2\pi a^2}{2\pi a L} = \frac{a}{L} \sim \frac{1}{6}$$

Hence $(1 - N) \doteqdot 0\cdot 2$.

From this calculation the fraction of the number of 2·62 keV. quanta which is absorbed in the counter is $N \doteqdot 0\cdot 80$ for argon or nitrogen/

nitrogen fillings.

In the case of hydrogen and helium μ is very small ($1 \cdot 5 \times 10^{-4}$ and $1 \cdot 02 \times 10^{-3}$ respectively) and so $N \doteqdot 0$. (It can be shown mathematically that $I \to \frac{1}{2\lambda}$ as $\lambda \to 0$).

Appendix II.

Factors Affecting the Accurate Measurement of a Count-rate.

Before the final experiments to determine absolute values of V were undertaken a preliminary investigation into the accurate measurement of the count-rate was carried out. The following factors were found to influence the value of n obtained.

1. Type of counter.

In principle a Geiger counter is a suitable instrument for determining n since only a numerical value is required. A conventional counter with guard tubes (but with no field adjusting tubes) was filled with $\sim$ 1 cm. alcohol + 10 cm.A and operated as a Geiger counter, the wire and guard tubes being at zero potential and the case at a negative voltage. An external γ-ray source gave the count-rate - applied voltage curve in fig. 36, (a). A plateau with a slope of 11·8%/ 100 volts was obtained. The same counter was then operated as a proportional counter with a filling of 10 cm. CH_4 + 70 cm. A. Using the same source the curve in fig. 36 (b) was obtained. The plateau is longer and very nearly flat; in addition, it was found that the background was $\sim$ 25% less than it was when the counter was operated as a Geiger counter. Because of these results it was decided to use a proportional counter for the measurement of n .
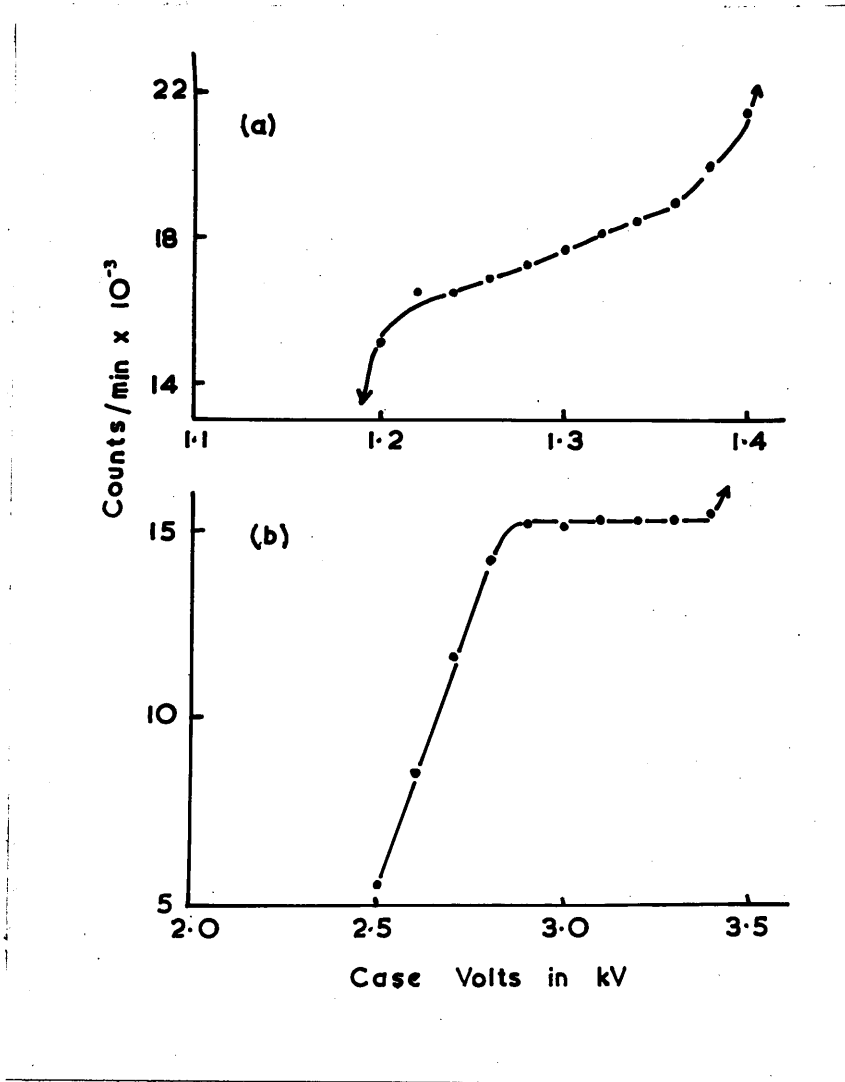
2./

<u>Fig. 36.</u>

Variation of count-rate with applied voltage.

(a) Geiger counter   (b) proportional counter.

2.   Type of scaler.

Two types of scaling unit were available for the counting
of pulses.   Type 1009, which contains a discriminator with a
variable bias, is a later model of type 200.   They will be
referred to in this section as "new scaler" and "old scaler"
respectively.   Preliminary work had been carried out using a
proportional counter connected to a new scaler with the
discriminator bias at its lowest setting of 5 V.   It was noted,
in the course of several experiments, that the height of plateau
obtained depended on the amplifier gain and the input circuit of
the amplifier.   A count-rate - applied voltage curve was plotted
using the two scalers in turn.   The old scaler was found to give
a plateau $\sim 4\%$ higher than that obtained using the new scaler.
An experiment with a Geiger counter showed that the two types of
scaler gave identical counting rates with the regularly sized
Geiger pulses.   Returning to the proportional counter
experiments it was found that the old scaler gave the same count-
rate at the two settings G.M. + and I.C. + (representing different
paralysis times) and the new scaler counting rate was also
constant for paralysis times from 0 to 20 μS.

The above experiments were carried out using an external
γ-ray source and it was thought that counts might be lost in the
case of the new scaler due to the paralysing of the input circuit
by/

by very large pulses.   X-rays from indium were used to give
pulses of one size, but it was found that the difference in
count-rate between the scalers remained almost constant.   In
order to limit the size of the pulses before they reached the
scaler a diode valve was included in the second last stage of the
amplifier.   Normally the amplifier had a push-pull output, but
the insertion of the diode necessitated the use of a one valve
output.   The input circuit of the main amplifier consisted of a
500 $\mu\mu$F condenser with a chain of four 5600Ω resistances to
ground.   The differentiating time constant was thus 12 μS ;
this could be changed to 3μS by shorting out three of the
resistors.

A systematic investigation was undertaken to find how the
count-rate varied with the differentiation time constant, the
amplifier gain and the diode bias, for the two scalers.   An
external γ-ray source was used with a proportional counter
operating at the middle of its plateau; the paralysis time
setting was 0 μS for both scalers.   There was a factor $\sim$ 4
between low and high gains.   It was found that a diode bias
$\sim$ 80V completely cut off all pulses.   Four main divisions
characterized by different diode biases were considered and the
results are tabulated below.

(i)/

(i) <u>Diode out of circuit completely. Push pull output.</u>

			Count-rate	
		New scaler		Old scaler
1.	12μS differentiation	(a) 20,667 (Low Gain)	21,281	(L.G.)
	time constant	(b) 21,379 (High Gain)	22,039	(H.G.)
2.	3 μS d.t.c.	(a) 20,806 (L.G.)	21,494	(L.G.)
		(b) 21,019 (H.G.)	21,547	(H.G.)

(ii) <u>Diode in circuit, one valve output. Diode bias zero, all</u>
<u>pulses passed without attenuation.</u>

			Count-rate	
		New scaler		Old scaler
1.	12μS d.t.c.	(a) 20,690 (L.G.)	21,296	(L.G.)
		(b) 20,521 (H.G.)	21,178	(H.G.)
2.	3 μS d.t.c.	(a) 20,923 (L.G.)	21,354	(L.G.)
		(b) 20,913 (H.G.)	21,476	(H.G.)

(iii) <u>Diode bias = 30 V.</u>

			Count-rate	
		New scaler		Old scaler
1.	12μS d.t.c.	(a) 21,200 (L.G.)	21,565	(L.G.)
		(b) 20,617 (H.G.)	21,369	(H.G.)
2.	3 μS d.t.c.	(a) 20,967 (L.G.)	21,243	(L.G.)
		(b) 21,006 (H.G.)	21,503	(H.G.)

(iv)/

(iv) <u>Diode bias = 75 V.</u>

			<u>New scaler</u>	Count-rate <u>Old scaler</u>
1.	12 μS	d.t.c.	(a) 20,980 (L.G.)	21,313 (L.G.)
			(b) 8,849 (H.G.)	39,500 (H.G.)
2.	3 μS	d.t.c.	(a) 21,145 (L.G.)	21,334 (L.G.)
			(b) 688 (H.G.)	21,487 (H.G.)

The standard deviation of the count-rate was $\sim$ 150 thus the count-rate for the old scaler can be seen to be sensibly constant with the exception of cases (i) <u>1</u> (b) and (iv) <u>1</u> (b). The first case is easily explained for with 12 μS d.t.c. and high gain the pulses were large and crowded together. Under these conditions the scaler might be expected to count multiple pulses and give a spuriously high count-rate. The second case is interesting for the following reason. With a diode bias of 75 V. , a 12 μS d.t.c. and low gain the pulse appeared to be $\sim$ 1 in. on the monitor screen. With high gain (case (iv) <u>1</u> (b)) the pulses almost disappeared into the base line which was rather unsteady. Under these conditions the old scaler counted spuriously fast. Pulses just appearing above the base line is the condition that obtains at the start of a plateau; this demonstration/

demonstration of a spuriously high counting rate may account
for the hitherto unexplained rise sometimes observed at the
beginning of a plateau.   This will be considered in more detail
later.

Discounting these two cases which are both exceptional
the old scaler count-rate is independent of amplifier conditions
and it is assumed to be correct.   With this assumption, it can
be seen that the count-rate given by the new scaler is often too
low and is dependent on amplifier conditions.   It was concluded
that a more accurate value of n would be obtained if an old scaler
type 200 was used.   To give optimum amplifier conditions a diode
bias of 30 V. was used with a 3 μS d.t.c. at high gain.

3.   Plateaux shapes.

A curious rise at the beginning of a plateau has sometimes
been noted.   Fig. 37 shows the count-rate - applied voltage
curve obtained using a proportional counter with an internal P_0
α -particle source.   Considering the evidence given above it is
likely that this rise is a spurious effect introduced by the
scaler.   In order to check this hypothesis and to ensure that a
true count-rate is obtained from the flat part of the plateau the
following experiment was carried out.   The shape of the pulses
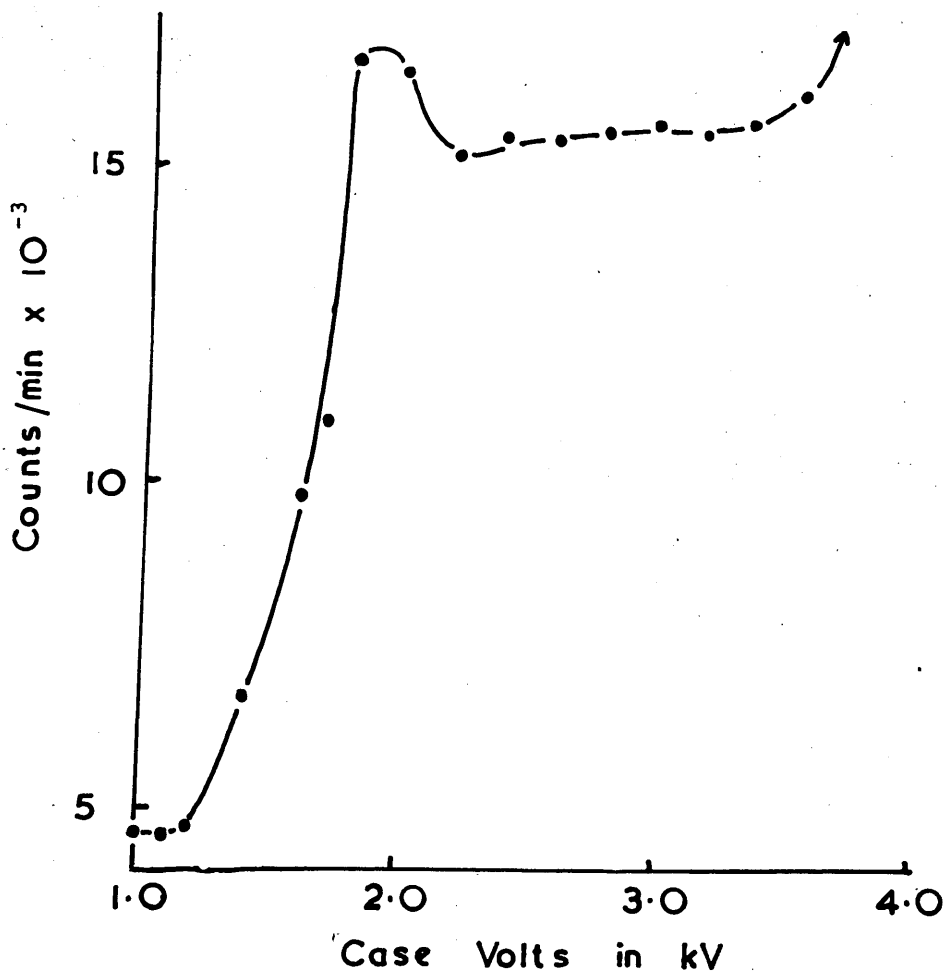was examined using a triggered cathode ray tube and they were
found/

<u>Fig. 37.</u>

Count—rate – applied voltage curve for Po ⍺ -particles
in a proportional counter.

found to be ~ 50 μS wide.   In order to simulate the
experimental conditions square pulses of 30 μ S width were fed
into the scaler from a pulse generator and the plateau shown in
fig. 38 was obtained.   A very marked peak is seen at the start
of the plateau.   That the long flat part of the curve gives a
true value of the count-rate was checked by an independent
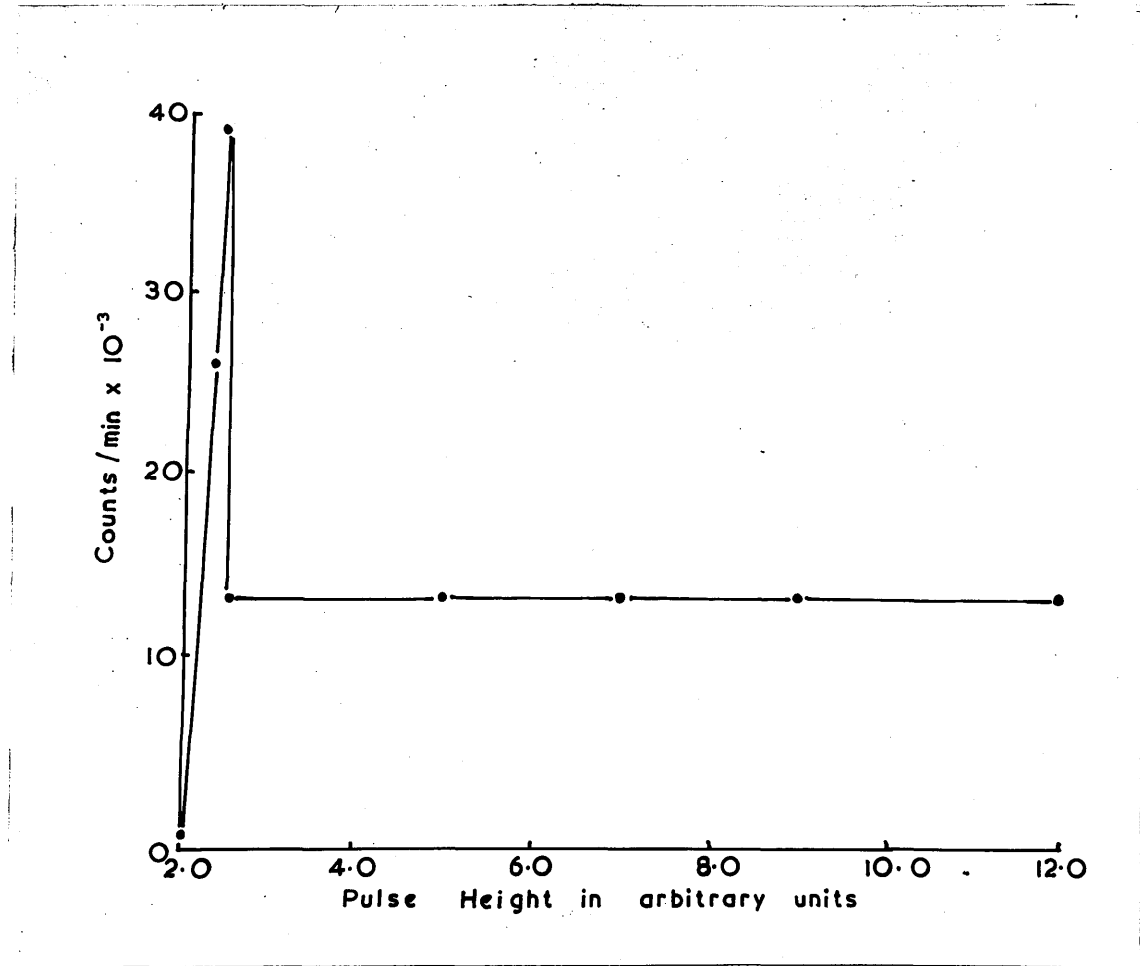frequency measurement of the pulse generator output.

Fig. 38.

Count-rate – pulse height curve for pulse generator
output.

References.

Alder, F., Huber, P. & Metzger, F. 1947 Helv. Phys. Acta 20, 234.

Anslow, G. 1925 Phys. Rev. 25, 484.

Bagge, E. 1937 Ann. Phys. Lpz. 30, 72.

Bakker, C. J. & Segré, E. 1951 Phys. Rev. 81, 489.

Bethe, H. 1930 Ann. Phys. Lpz. 5, 325.

Binks, W. 1936 Reports on Progress in Physics, 3, 347.

Bohr, N. 1948 Danske Viden. Selskab. Mat.-Phys. Med. 18, No. 8.

Born, M. 1935 Atomic Physics.

Breunig, E. 1936 Ann. Phys. Lpz. 25, 467.

Buchmann, E. 1928 Ann. Phys. Lpz. 87, 509.

Chang, W. Y. 1946 Phys. Rev. 69, 60.

Cockroft, A. L. & Curran, S. C. 1951 Rev. Sci. Instrum. 22, 37.

Cockroft, A. L. & Valentine, J. M. 1950 J. Sci. Instrum. 27, 262.

Compton, A. H. & Allison, S. K. 1936 X-rays in Theory and
                                        Experiment.

Cranshaw, T. E. & Harvey, J. A. 1948 Canad. J. Res. A, 26, 243.

Crowther, J. A. & Orton, L. H. H. 1930 Phil. Mag. 10, 329.

Crowther, J. A. & Orton, L. H. H. 1932 Phil. Mag. 13, 505.

Curran, S. C., Angus, J. & Cockroft, A. L. 1949,a Phil. Mag. 40,36.

Curran, S. C., Angus, J. & Cockroft, A. L. 1949,b Phil. Mag. 40,929.

Curran, S. C., Cockroft, A. L. & Insch, G. M. 1950 Phil. Mag. 41,517.

Dainton, F. S., 1948 Reports on Progress in Chemistry 45, 5.

Dick, L., Falk-Vairant, P. & Rossel, J. 1947 Helv. Phys. Acta 20,357.

Eisl/

Eisl, A. 1929 Ann. Phys. Lpz. $\underline{3}$, 277.

Ewan, G. J. & Ross, M. A. S. 1952 Nature $\underline{170}$, 760.

Fano, U. 1946 Phys. Rev. $\underline{70}$, 44.

Freund, L. 1935 Ann. Phys. Lpz. $\underline{22}$, 748.

Gaertner, O. 1929a Ann. Phys. Lpz. $\underline{2}$, 94.

Gaertner, O. 1929b Ann. Phys. Lpz. $\underline{3}$, 329.

Gaertner, O. 1931a Ann. Phys. Lpz. $\underline{10}$, 825.

Gaertner, O. 1931b Ann. Phys. Lpz. $\underline{11}$, 648.

Gaertner, O. 1933 Ann. Phys. Lpz. $\underline{16}$, 613.

Gaertner, O. 1934/5 Ann. Phys. Lpz. $\underline{21}$, 564.

Gaertner, O. 1935 Ann. Phys. Lpz. $\underline{23}$, 255.

Gerbes, W. 1935 Ann. Phys. Lpz. $\underline{23}$, 648.

Gerbes, W. 1937 Ann. Phys. Lpz. $\underline{30}$, 169.

Gray, L. H. 1936 Proc. Roy. Soc. A $\underline{156}$, 578.

Gray, L. H. 1944 Proc. Camb. Phil. Soc. $\underline{40}$, 72.

Gurney, R. W. 1925 Proc. Roy. Soc. A $\underline{107}$, 332.

Hacman, D. & Haxel, O. 1943 Z.Phys. $\underline{120}$, 486.

Haeberli, W., Huber, P. & Baldinger, E. 1950 Helv. Phys. Acta $\underline{23}$, 481.

Haeberli, W., Huber, P. & Baldinger, E. 1952 Helv. Phys. Acta $\underline{25}$, 467.

Hanna, G. C. 1950 Phys. Rev. $\underline{80}$, 530.

Heitler, W. 1944 The Quantum Theory of Radiation.

Holloway, M. G. & Livingston, M. S. 1938 Phys. Rev. $\underline{54}$, 18.

Huber, P., Baldinger, E. & Haeberli, W. 1950 Helv. Phys. Acta $\underline{23}$, Suppl. III, 85.

Insch/

Insch, G. M. & Curran, S. C. 1951 Phil. Mag. 43, 892.

Jesse, W. P., Forstat, H. & Sadauskis, J. 1950 Phys. Rev. 77, 782.

Johnson, J. B. 1917 Phys. Rev. 10, 609.

Kirkwood, D. H. W., Pontecorvo, B. & Hanna, G. C. 1948 Phys. Rev. 74, 497.

Kulenkampff, H. 1926 Ann. Phys. Lpz. 80, 91.

Landhold - Börnstein, 1950 Tables, Series 6, Vol. 1.

Lea, D. E. 1946 Actions of Radiations on Living Cells.

Lehmann, J. F. & Osgood, T. H. 1927 Proc. Roy. Soc. A115, 609.

Lehmann, J. F. 1927 Proc. Roy. Soc. A 115, 624.

Livingston, M. S. & Bethe, H. A. 1937 Rev. Mod. Phys. 9, 245.

Maze, R. 1946 J. de Phys. et le Rad., ser. 8, 7, 164.

Meitner, L. 1926 Naturwiss 14, 1199.

Mott, N. F. & Massey, H. S. W. 1949 The Theory of Atomic Collisions.

Naidu, R. 1934 Ann. Chim. (Phys.) 1, 72.

Nicodemus, D. B. 1946 Thesis, Stanford University.

Pigge, H. 1934 Ann. Phys. Lpz. 20, 233.

Pontecorvo, B. 1950 Helv. Phys. Acta 23, Suppl. III, 97.

Rose, M. E. & Jackson, J. L. 1949 Phys. Rev. 76, 1540.

Rutherford, E., Chadwick, J. & Ellis, C. D. 1930 Radiations from Radioactive Substances.

Schmieder, K. 1939 Ann. Phys. Lpz. 35, 445.

Schmitz, W. 1928 Phys. Z. 29, 846.

Sharpe, J. 1952 Proc. Phys. Soc. 65, 860.

Steenbeck/

Steenbeck, M. 1928 Ann. Phys. Lpz. <u>87</u>, 811.

Stetter, G. 1943 Z. Phys. <u>120</u>, 639.

Taylor, T. S. 1911 Phil. Mag. <u>21</u>, 571.

Taylor, T. S. 1913 Phil. Mag. <u>26</u>, 402.

Townsend, J. 1947 Electrons in Gases.

Valentine, J. M. 1952 Proc. Roy. Soc. A<u>211</u>, 75.

Valentine, J. M. & Curran, S. C. 1952 Phil. Mag. <u>43</u>, 964.

Weimer, P. K., Kurbatov, J. D. & Pool, M. L. 1944 Phys. Rev. <u>66</u>,
209.

Wilhelmy, E. 1933 Z. Phys. <u>83</u>, 341.

Wilkinson, D. H. 1950 Ionization Chambers and Proportional
Counters.

Wilson, C. T. R. 1923 Proc. Roy. Soc. A <u>104</u>, 200.